Spatial Decision Support System for Coastal Flood Management in Victoria, Australia.

Thesis submitted in fulfilment of the requirements for the degree of Doctor of Philosophy

Sultana Nasrin Baby

BSc (Geography and Environment), Dhaka University, Dhaka, Bangladesh
MSc (Geography and Environment), Dhaka University, Dhaka, Bangladesh
M.A (Geography and Environmental Science), Monash University, Melbourne, Australia

School of Science

College of Science, Engineering and Health

RMIT University

January 2020

Declaration

I certify that, except where due acknowledgement has been made, the work is that of the author alone; the work has not been submitted previously, in whole or in part, to qualify for any other academic award. The content of the thesis is the result of work which was carried out since the official commencement date of the approved research program. Any editorial work, paid or unpaid, carried out by a third party is acknowledged; and, ethics procedures and guidelines have been followed. I acknowledge the support I have received for my research through the provision of an Australian Government Research Training Program Scholarship.

SULTANA NASRIN BABY
14 January 2020

Acknowledgement

I want to thank every one of the individuals who supported me during my research. Without their assistance, I couldn't have finished this thesis.

First, I would like to thank the Almighty Allah for the uncountable blessing that He has bestowed upon me. I dedicate this thesis to my late father, Md Alauddin Sikder. I miss him all the time, but I am pleased to know that he saw my thesis process through to its completion. Without his mental support and encouragement, it would have been impossible for me to finish my thesis.

I am profoundly appreciative to my supervisor, Associate Professor Colin Arrowsmith, whose generous support and assistance from the crucial stage to the last phase of my PhD. enabled me to extraordinarily improve my research abilities.

I additionally want to thank my co-supervisor, Associate Professor David Mitchell who gave extremely helpful support. I also want to demonstrate my gratefulness to another co-supervisor, Senior Lecturer Dr Gang-Jun Liu for his technical writing support.

I thank my mother, brothers and sisters which enabled me to understand my very own potential. All the help they have given me throughout the years was the best blessing anybody has ever given me. Without my family, I may never have gotten to where I am today.

I am appreciative to the Bass Coast Shire Council's, Geographic Information System (GIS) Team. Special thanks and gratitude go to Nahala Abbas, PhD understudy of Central Queensland University for his magnificent help amid my research.

Thanks to Hugh Kirkman, for his professional editing services. I owe my deepest gratitude to my husband, Ahmed, and my beloved daughter Tayeba, for their support and patience. I am much obliged to the Australian Government for assisting my PhD endeavours and RMIT University Geospatial Department for its help.

Abstract

Coastal climate impact can affect coastal areas in a variety of ways, such as flooding, storm surges, reduction in beach sands and increased beach erosion. While each of these can have major impacts on the operation of coastal drainage systems, this thesis focuses on coastal and riverine flooding in coastal areas.

Coastal flood risk varies within Australia, with the northern parts in the cyclone belt most affected and high levels of risk similar to other Asian countries. However, in Australia, the responsibility for managing coastal areas is shared between the Commonwealth government, Australian states and territories, and local governments. Strategies for floodplain management to reduce and control flooding are best implemented at the land use planning stage. Local governments make local decisions about coastal flood risk management through the assessment and approval of planning permit applications. Statutory planning by local government is informed by policies related to coastal flooding and coastal erosion, advice from government departments, agencies, experts and local community experts.

The West Gippsland Catchment Management Authority (WGCMA) works with local communities, Victorian State Emergency Services (VCSES), local government authorities (LGAs), and other local organizations to prepare the West Gippsland Flood Management Strategy (WGFMS). The strategy aims at identifying significant flood risks, mitigating those risks, and establishing a set of priorities for implementation of the strategy over a ten-year period.

The Bass Coast Shire Council (BCSC) region has experienced significant flooding over the last few decades, causing the closure of roads, landslides and erosion. Wonthaggi was particularly affected during this period with roads were flooded causing the northern part of the city of Wonthaggi to be closed in the worst cases. Climate change and increased exposure through the growth of urban population have dramatically increased the frequency and the severity of flood events on human populations.

Traditionally, while GIS has provided spatial data management, it has had limitations in modelling capability to solve complex hydrology problems such as flood events. Therefore, it has not been relied upon by decision-makers in the coastal management sector. Functionality improvements are therefore required to improve the processing or analytical capabilities of GIS in hydrology to provide more certainty for decision-makers**.**

This research shows how the spatial data (LiDAR, Road, building, aerial photo) can be primarily processed by GIS and how by adopting the spatial analysis routines associated with hydrology these problems can be overcome. The aim of this research is to refine GIS-embedded hydrological modelling so they can be used to help communities better understand their exposure to flood risk and give them more control about how to adapt and respond. The research develops a new Spatial Decision Support System (SDSS) to improve the implementation of coastal flooding risk assessment and management in Victoria, Australia. It is a solution integrating a range of approaches including, Light Detection and Ranging (Rata et al., 2014), GIS (Petroselli and sensing, 2012), hydrological models, numerical models, flood risk modelling, and multi-criteria techniques.

Bass Coast Shire Council is an interesting study region for coastal flooding as it involves (i) a high rainfall area, (ii) and a major river meeting coastal area affected by storm surges, with frequent flooding of urban areas. Also, very high-quality Digital Elevation Model (DEM) data is available from the Victorian Government to support first-pass screening of coastal risks from flooding. The methods include using advanced GIS hydrology modelling and LiDAR digital elevation data to determine surface runoff to evaluate the flood risk for BCSC. This methodology addresses the limitations in flood hazard modelling mentioned above and gives a logical basis to estimate tidal impacts on flooding, and the impact and changes in atmospheric conditions, including precipitation and sea levels. This study examines how GIS hydrological modelling and LiDAR digital elevation data can be used to map and visualise flood risk in coastal built-up areas in BCSC. While this kind of visualisation is often used for the assessment of flood impacts to infrastructure risk, it has not been utilized in the BCSC.

Previous research identified terrestrial areas at risk of flooding using a conceptual hydrological model (Pourali et al., 2014b) that models the flood-risk regions and provides flooding extent

maps for the BCSC. It examined the consequences of various components influencing flooding for use in creating a framework to manage flood risk. The BCSC has recognised the benefits of combining these techniques that allow them to analyse data, deal with the problems, create intuitive visualization methods, and make decisions about addressing flood risk.

The SDSS involves a GIS-embedded hydrological model that interlinks data integration and processing systems that interact through a linear cascade. Each stage of the cascade produces results which are input into the next model in a modelling chain hierarchy. The output involves GIS-based hydrological modelling to improve the implementation of coastal flood risk management plans developed by local governments.

The SDSS also derives a set of Coastal Climate Change (CCC) flood risk assessment parameters (performance indicators), such as land use, settlement, infrastructure and other relevant indicators for coastal and bayside ecosystems. By adopting the SDSS, coastal managers will be able to systematically compare alternative coastal flood-risk management plans and make decisions about the most appropriate option. By integrating relevant models within a structured framework, the system will promote transparency of policy development and flood risk management.

This thesis focuses on extending the spatial data handling capability of GIS to integrate climatic and other spatial data to help local governments with coastal exposure develop programs to adapt to climate change. The SDSS will assist planners to prepare for changing climate conditions. BCSC is a municipal government body with a coastal boundary and has assisted in the development and testing of the SDSS and derived many benefits from using the SDSS developed as a result of this research. Local governments at risk of coastal flooding that use the SDSS can use the Google Earth data sharing tool to determine appropriate land use controls to manage long-term flood risk to human settlement. The present research describes an attempt to develop a Spatial Decision Support System (SDSS) to aid decision makers to identify the proper location of new settlements where additional land development could be located based on decision rules. Also presented is an online decision-support tool that all stakeholders can use to share the results.

Table of Contents

List of Figures

List of Tables

Preface

This PhD thesis contains eight Chapters, of which Chapter 1, 2, 4, 5, have been submitted as journal articles. A part of chapter 6 and 7 was under revision for a journal article. A part of chapter 4 has been published as a conference paper. Different parts and concepts of chapter 5 have been published as a conference paper and for a journal publication. A part of chapter 2 has been accepted for publication. In addition, a journal article based on the literature review has also been published. This journal article and the conference paper have not been included in the thesis to be consistent with the university standards and guidelines. However, a substantial amount of the published and accepted papers has been used in the thesis. The major research of these publications was carried out independently with the co-authors contribution in the form of supervision from experimental design to manuscript writing. The citations of the published, accepted and in-revision chapters are as follows:

Chapter 1

Baby S. N (2018) Spatial Decision Support System for Coastal Zone Management under a Changing Climate in Victoria, Australia, Published by Scientific Research Publishing

Chapter 2

Baby S. N (2018) Marine Spatial Planning and Ecosystem-Based Management" has been successfully submitted online and is being considered for publication in Australasian Journal of Environmental Management.

Chapter 4

Baby S. N (2013) Local Government perspective on Climate Change as an added consideration in maintaining and extending drainage infrastructure.

Chapter 5

Baby S. N (2018) Climate Change Impacts on Water Resources of Ary Creek, Inverloch, Victoria, publish by Journal of Civil Engineering and Architecture.

Chapter 7

Baby S N (2018) Make better decision through web-based climate change spatial tool.

Conference Presentations:

Baby S N (2017) “Spatial decision support system for coastal zone management under a changing climate in Victoria, Australia”, 2nd International Conference on, Coastal Zones, July 17-18, 2017 Melbourne, Australia.

Baby S N (2017) “Monitoring Simulation for Flood Risk Prediction Using 3D analysis and SWAT in Ary Creek Watershed” Soil and Water Sciences 2nd Annual Congress on October 22-23, 2018, Berlin, Germany.

List of Abbreviations

ABS	Australian Bureau of Statistics
AHD	Australian Height Datum
BCSC	Bass Coast Shire Council
BSM	Blue Spot Model
BOM	Bureau of Meteorology
CFM	Coastal flood management
CMA	Catchment Management Authority
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DEM	Digital Elevation Model
DELWP	Department of Environment, Land, Water and Planning
DPCD	Department of Planning and Community Development
DSE	Department of Sustainability and Environment
GIS	Geographical Information System
IDW	Inverse Distance Weight
IWM	Integrated Water Management
LiDAR	Light Detection and Ranging
LSIO	Land Subject to Inundation Overlay
MGA	Map Grid of Australia
MW	Melbourne Water
SAGA	System for Automated Geoscientific Analysis
SDI	Spatial Data Infrastructure
SDSS	Spatial Decision Support System
SES	Victorian State Emergency Service
SWAT	Soil water assessment tool
TIN	Triangular Irregular Network
TWI	Topographic Wetness Index
VFMS	Victorian Floodplain Management Strategy
VPPs	Victorian Planning Provisions
SDI	Spatial Data Infrastructure
WGCMA	West Gippsland Catchment Management Authority
WSUD	Water Sensitive Urban Design

Chapter 1

1 Introduction

Coastal flooding may occur due to changes in global sea levels but may also occur due to sudden stowage of seawater in creeks, sounds and lagoons due to long-lasting storms. Coastal flood risk varies within Australia, with the northern parts in the cyclone belt most affected and high levels of risk similar to other Asian countries. In Australia, when storms are heavy and from the predominant wind direction, low-lying coastal areas are at risk of being flooded. Geographic Information System (GIS) based hydrology models help local government planners in assessing areas that might be threatened due to a sudden or a long-term impact. GIS is concerned with the outline, clarification, prediction and strategies at a variety of geographic scales. GIS provides well-established processes for mapping and spatial analysis of the real world (Longley et al., 2005). Hydrological models estimate and allow for an understanding of hydrologic processes and the behaviour of hydrologic structures.

GIS and hydrological modelling have developed separately with few interactions until recently. Traditionally, there was little research on the integration of GIS and hydrological modelling. However, in recent years, GIS has become a highly valued tool for hydrological modelling. Experts and managers have come to realize the importance and benefits of combining GIS and hydrological modelling techniques to allow them to analyse data, deal with problems, create intuitive visualization methods, and make decisions. The overall aim of this research is to integrate GIS with hydrological modelling and multi-source spatial data systems. This chapter discusses the rationale and objectives of this research and is split into six subsections. First, the background is discussed, followed by a statement of the research problem. The third section justifies the research. The next two sections describe the methodological design and the thesis outline. Finally, the research questions are outlined.

1.1 Background of the study

The coastal settlements in Victoria face increasing climate-related risk. Victorian coastal land and marine waters stretch for nearly 2000 kilometres and contain spectacular coastlines and

important natural features. Most of the Victorian coast (96%) is public land (Wescott, 1998), in contrast to coastal regions in most other Australian States. The coast is considered to be the meeting between sea and land and this varies over time (Aurrocoechea and Pethick, 1986). For legal purposes, the coastal land boundary can be defined by the mean high tide – resulting in a line that forms the coastal boundary. To assess the landscape, it can be observed as the area that can be seen from the beach—in some cases, a limited coastal area is bordered by cliffs (Caton and Harvey, 2010). The Victorian Coastal Strategy defines the coastline as "the sea and the seabed to the state limit of three nautical miles or 5.5 km; land and inland waters in the coastal catchment" (Wheeler et al., 2011).

Over 80% of Victorians live within the coastal strip (Wescott, 1998). The migration to Victorian coastal urban areas was an important trend throughout the twentieth century (Nicholls, 2004, Small and Nicholls, 2003), and Victoria has a number of cities located along the coast. Melbourne itself is situated on Port Phillip Bay, and the population of Melbourne was 4.8 million in 2018. Research in 2015 showed that almost 300,000 Victorians were considering moving to the coast in the subsequent five years (Mason, 2015).

The City of Greater Geelong, the Shires of Surf Coast and Bass Coast Shire Council (BCSC) are the coastal councils near Melbourne. The BCSC population estimate for 2018 is 34,447 and is forecast to grow to 46,429 by 2036—a change of 34.78% between 2018 and 2036 (Lethlean et al., 2017). The coastal areas of Victoria are likely to face many issues in the future regarding climate change and associated sea level rise (SLR) scenarios (e.g. see Commonwealth of Australia, 2012; Government, 2009; IPCC, 2007). For example, it was estimated in 2009 that between 27,600 and 44,600 buildings in Victoria, with a value of between AUD 6.5 and 10.3 billion, may be at risk of flooding with SLR of 1.1 meters, and storm tide associated with a 1: 100-year storm event Government (2009).

Despite the importance of planning for climate change and variability (Vasey-Ellis, 2009) in Victoria, a lack of information regarding possible coastal climate change scenarios represents a key decision-support limitation for coastal flooding. Coasts are dynamically changing systems that are often evolving.

The hazard risk in Victorian coastal areas is high because many towns and cities are situated along the coast, and in summer tourists increase the local population. Therefore, it is essential to understand how development can be controlled in coastal zones (Caton and Harvey, 2010). Significant modifications to coastal areas are caused by human land use and by natural forces (Harvey, 2017). For instance, coastal wetlands can be lost through SLR and urban development.

Coasts are eroded by wave activity and human development such as harbour development. Dunes are destabilized by storms or fires, and by vehicle impact. A typical issue in coastline management is how to isolate climate change impacts from human-induced change. The change in land use caused by population growth can alter water flows in such a way as to increase the risk of flooding. An example of this is the rise in flow peaks following the conversion of the natural soil to less permeable surfaces (Garcia and Loáiciga, 2014). Moreover, the rapid development of the Victorian coastline and increased population will increase the economic, social and natural effects of flooding (Lempert et al., 2013).

The 2016 Victorian Floodplain Management Strategy (VFMS) is the strategy for managing floodplains and reducing flood hazards in urban and rural communities and providing guidance on riverine, flash and coastal flooding (White, 2016). The Strategy aligns with the Victorian Government's responses to the *Inquiry into Flood Mitigation Infrastructure in Victoria*. It also aligns with the broader emergency management framework set out in the *Emergency Management Act 2013*. The VFMS coordinates local floodplain management with the Victorian Coastal Strategy 2014 and the Victorian Waterway Management Strategy 2013.

Victorian local government planning schemes include overlays that prevent building over flood-prone areas and those at risk of storm surge flooding, riverine flooding, stormwater runoff flooding, overland flash flooding, and tidal flooding. The VFMS (Charteris et al., 2001) provides for structural flood risk reduction (for example levees, impeding basins, drains and

floodway), as well as non-structural measures (land use arranging zones and overlays, and set-backs, protection, cautioning frameworks, instruction and mindfulness raising).

Local knowledge is needed when planning for prevention and mitigation of the effects of flooding and is best managed using sharing responsibility. For example, local governance flood overlays are of limited accuracy – especially where the flood plain is relatively flat. Councils, Melbourne Water (Habib et al., 2005) and Catchment Management Authorities (CMAs) are all key stakeholders in the floodplain strategy (Council, 2008). Coastal management involves agencies, government and consultants working together to manage floodplains through land use planning, emergency management and ecological administration. The management of floodplains also requires sharing of flood hazard data that can be used by all stakeholders for improved floodplain management, flood alerts and responses (Trkman and McCormack, 2009).

There are different parts to the VFMS. The creation of flood overlay plans serves to alert decision-makers about the risks of flooding when deciding on planning permit applications. To avoid future hazard impact, the flood overlays are controls that identify flood risk and inform future land development decisions and ensures developments and infrastructure are not built in areas at high risk of flooding. The VFMS recommends developing enough benchmarks (survey ground marks) to allow measurements of changes in sea levels (Hansson et al., 2008). To reduce existing risks the VFMS also addresses the institutional structures and coordination needed to reduce the hazard risk and result of floods, and how flood warning will operate. The VFMS also outlines how the approaches, activities and duties should be executed at the state and local levels (Cush, 2016). A challenge for flood management is how to acquire accurate data to support decisions that decrease the impact of flood events. As some key data is lacking, decision-makers must utilize existing recorded material (for example information held by a community member, expert information or theoretical models).

At the organisational level, the challenge for decision-making is to reduce the probability of flooding and its effects on coastal land and people. Managing flood risk is, therefore one of the CMA and LGAs' most critical duty. It is a statutory requirement of the CMA and LGA to adopt flood legislation, flood risk evaluations and flood mapping to deliver risk management

frameworks for emergency preparedness based on science (Hardaker and Collier, 2013). This theory underpins the BCSC post-disaster assessments which recognized that the combination of GIS and hydrology is needed to improve the prediction of flooding in the BCSC.

1.2 Comparison of Arc Hydro and Soil Water Assessment Tool

According to Burrough and McDonnel (1998), GIS is a tool for information creation, storage, and investigation. GIS has played an important supporting role in science during the previous two decades. GIS provides reliable and consistent estimation, mapping and investigation of the present reality (Longley et al., 2005). Further, hydrological analysis and exercises are difficult without the utilization of GIS, and the rapid advancement in GIS means it has much to offer for analysing spatial data in hydrological models (Chow et al., 1988, Clark, 1998). Hydrological modelling using LiDAR and GIS can allow flooding projection models to be developed in catchments (Merwade et al., 2008, Gallegos et al., 2009). When developing complex hydrological models to assess flood risks in catchments, Digital Elevation Models (DEMs) are utilized in a GIS to obtain basic geographical factors - for example, stream systems, stream headings, catchment geometry in terms of distributed information on land use, soil, and climate information (Siart et al., 2009). GIS is used to extend both subjective and quantitative effects of floods and runoff (Wang et al., 2011), and spatial-based hydrological models have been effectively used for flood investigation in shoreline areas (Sarker and Sivertun, 2011, Zerger and Wealands, 2004).

Hydrologic models have performed a significant role in coastal flood management for a long time. Reproduction models are normally used to anticipate the effects of proposed flood risk potential under climate change situations and to support the manager's decision-making (Messner and Meyer, 2006). However, GIS is rarely the existing environment in which coastal flood system study methods are implemented (Djokic and Maidment, 1993). This is particularly important in the field of coastal floods management. Decision-makers rely on scientific models to give knowledge about flooding and SLR. Hydrological modelling could benefit from the spatial tools and capacity of GIS, and GIS could benefit from the numerical data (Xu et al., 2001).

The IPCC predictions of climate change leading to more frequent and severe flooding events over the coming decades; means there is uncertainty around the precision of these forecasts (Field et al., 2012). Future development may likewise influence flood hazards. Given the accuracy of LiDAR and GIS-based hydrological data, they are particularly suited to assessing infrastructure and roads for flood hazard risk.

This research used advanced GIS hydrology modelling and LiDAR digital elevation data to determine surface runoff and to evaluate the flood risk for BCSC. This methodology addressed the above knowledge gaps in flood hazard modelling and gives a logical basis to estimate the ebb and flow of flooding and the impact and changes in atmospheric conditions, including precipitation and sea levels. This study examines how GIS hydrologic modelling and LiDAR DEM data can be used to evaluate flood calculations and mapping in coastal built-up areas in BCSC. While this kind of visualizations of flood maps is suited to flood predictions and to assess infrastructure risk, it has not been previously utilized in the BCSC. Previous research identified the risk of flooding in terrestrial areas using a conceptual hydrological model (Pourali et al., 2014b) that models the flood-prone regions and flood risk maps for the BCSC.

This research gap was recognized by the BCSC which then developed a research plan to extend the previous research supported by the BCSC to include DEM derived from LiDAR data (Pourali et al., 2014b). The research aims include:

- Incorporation of stormwater flows mapping into land use and land development decision making.
- Management of flooding and drainage to mitigate risk to the community and the environment.
- An evaluation of the available data in the BCSC (regarding the Local Government Spatial Strategy– v2.2).
- An evaluation of the IT barriers for the spatial information managers in the Department of Environment and Primary Industry (DEPI) computer labs and other key users (Rajabifard et al., 2002) and

- An evaluation of the improvement in the use of advanced spatial information along the BCSC coastline. An interface was built to provide information to all stakeholders.

This laid the foundation for this research supporting the GIS users among the decision support teams.

This research aims to develop a ***Spatial Decision Support System for Coastal Flood Management in Victoria, Australia.*** This involved developing a GIS-based hydrological model to support the implementation of the coastal risk-based floodplain management strategy.

The BCSC was chosen as a pilot study area to implement an evaluation of spatially distributed hydrological models and screening methods to assess flood risk on buildings and roads. High-resolution LiDAR data and information on crowdsourcing are used. This research aimed to evaluate new developments and therefore analyse the applicability of two of the most well-known models in hydrological modelling: ArcHydro is an ArcGIS extension (Hydro Data Model tool) and the ArcSWAT is an ArcGIS extension and interface for SWAT (Soil and Water Assessment Tool) visualisation tool. ArcSWAT is generally easier to use for those with little GIS knowledge, and ArcHydro is more flexible and provides more options. While other GIS platforms such as the QGIS extension QSWAT could also have been chosen, the ArcGIS tools were chosen as they allow better customisation using python and geodata.

Flood impact visualisation continues to progress. The GIS-based hydrology model and screening methods to assess coastal flood risk will help develop a flood model visualisation suited to both expert and non-expert users. This research aims to support the development of a coastal flooding geo-database. The spatial information display outputs will allow coastal inundation forecasts to be provided to expert and non-expert end-users (Hine et al., 2017). Expert end-users are commonly GIS professionals, designers and modellers who are likely to benefit from developments in visualisation tools. Non-expert end-users are recognized as professionals, leaders and arrangement producers who might utilize the outputs of this research but not need the more technical outputs, such as the coastal drainage system, runoff, SLR,

overland flow, and discharge and from the deepwater circulated aground to the coast in the study area.

The models developed in this thesis are similar because each one involves a watershed visualisation with an interface to GIS. The models vary in how they support decisions about local government housing and infrastructure, and the information on the watershed. This allows consideration of which visualisation provided the best model of the watershed. When the models were run, the outcomes were contrasted with genuine field information with confirmed accuracy and usability. The two models enabled an examination of different watershed parameters. The research found that the ArcSWAT demonstration enabled scientists to use more physical information than the ArcHydro model, resulting in a more precise representation of the watershed, particularly for smaller basins such as Ayr Creek, Inverloch, BCSC. The ArcHydro model excels in data management, making it a better choice when it is necessary to collect and include large amounts of data in the model (for example with large water basins like that of Inverloch). ArcSWAT is easier to use for those with little GIS knowledge and ArcHydro is more flexible.

1.3 Research Formulation

1.3.1 Declaration of Research Problem

During the last decade, there has been tremendous development in Hydrologic Modelling using GIS. The uses of digital terrain models have shown their potential to undertake hydrological analysis. As mentioned earlier, mathematical hydrologic models have existed for more than a century. Darcy's Law (the fundamental equation governing groundwater flow) was discovered in 1856, the St. Venant equations describing unsteady open channel flow were developed in 1871, and description of the flow of water has continued to develop. During the 1950s Digital Terrain Models were developed and used for various geoscience applications. Computer models began to appear by the mid of 1960s, first for surface water flow and sediment transport, then in the 1970s for surface water quality and groundwater flow, then in 1980s for groundwater transport. During the 1990s hydrologists increasingly realised the utility of incorporating GIS with hydrologic modelling (Grover, 1999).

A key theme of the principal global conference on GIS and hydrology modelling held in Boulder, Colorado, on September 1991 (Djokic and Maidment, 1993), was about the lack of scientific case studies integrating the two areas of research (Djokic and Maidment, 1993, Mallawaarachchi et al., 1996). Some research in North America and Europe concentrated on the improvement of spatial modelling and visualisation capacities of GIS innovation during the previous 10 years (Goodchild, 2003). The use of GIS along with hydrological visualisation as part of this wider research agenda. Despite different GIS visualisation approaches being used the general strategy was appropriate (Sui et al., 1999). The integration of GIS with hydrological modelling has many applications depending on the type of GIS-based visualisations needed (Sui and Maggio, 1999). However, little has been progressed, and in part, this thesis sets out to redress some of the gaps that were discussed at the Boulder meeting in 1991.

For example, in contrast to many natural phenomena, hydrological modelling has well-established practices and approaches used by hydrologists. However, the way this has been integrated with GIS has varied across Australian jurisdictions. In New South Wales, South Australia, and Victoria the research focused on the use of hydrological models integrated with GIS in the local planning of land use at risk of flooding and the management of natural resources (Pourali et al., 2014b, Mallawaarachchi et al., 1996, Chiew et al., 2008). Pourali et al. (2014b) created GIS and Hydrological models to assess the impact of stormwater systems on overland flow mapping. The Topographic Wetness Index (TWI) was additionally used to make local level decisions at times of flooding and predict future flooding (Pourali, 2014). This examination developed new spatial information to improve GIS and hydrological visualisation to support coastline flood risk management.

GIS data modelling and hydrological decision support systems are intended to help decision-makers solve complex spatial issues and improve (a) analytical and spatial modelling capacity, (b) the provision of spatial and hydrological information to managers, (c) domain learning, (d) hydrological visualisation capacities, and (e) reporting ability (Sugumaran and Degroote, 2010). These DSS are especially useful in areas of high levels of flood risk.

Hydrological and pressure-driven models are also considered about their potential to support Spatial Decision Support Systems (SDSS), and their usefulness to flood managers (Rata et al., 2014). The use of SDSS is also relevant to groundwater systems, e.g. SLR, storm surge flooding, changes in water quality, the decrease of groundwater level and saltwater intrusion in the aquifer. The SDSS integrates three different components: i) a geodatabase for the management of all available data used for the application and their metadata, ii) an automated customized tool for the application of the methodology, iii) a Graphical User Interfaces (GUI) that simplifies the interaction of the final user with the system and simplifies the understanding of results (Shneiderman, 2010).

In the absence of relevant policy implementation and program capacity-building support, complex intertwined socio-technical factors, e.g., political, organizational/institutional, social and economic driving forces, can also act as major constraints to the effective development of digital spatial information and enabling technology. A range of such constraints were identified by Campbell and Masser (1995); Cornelius and Medyckyj-Scott (1991); de Man and van den Toorn, (2002); Obermeyer and Pinto, (2008); Pinto and Azad (1994); Reeve and Petch (1999); Schultz et al., (1987); Somers (1998), and Tomlinson (2007). If the necessary spatial information to implement the Victorian Coastal Management Act 1995 program is to be developed, institutional capacities and arrangements must be evaluated to enable effective technology diffusion and adoption.

The current state of spatial data integration may be adequate for servicing the information needs of decision-makers within a narrowly defined coastal area context. However public policy, linked to policies about sustainability in natural resources exploitation, has long called for the implementation of a wider coastal area approach. It seems that policies are framed in ways that take the evolution of data and information up-grade from coastal climate change in coastal flooding for granted but this is an important issue. This leads to further consideration from which a statement of research questions and objectives can evolve.

1.3.2 Research Aim and Research Questions

There are gaps between "spatial industry" (Douglas et al., 2008), flood policies and practice. The objective of this thesis is to discuss the current practices and existing problems, consider the prospects for the application of GIS in hydrologic modelling, and understand how GIS has influenced hydrological research.

This study is an attempt to better understand the application of GIS to hydrology in coastal locations and to develop appropriate tools for predicting coastal flooding. The research investigates two GIS applications: Arc Hydro (ArcGIS Hydro Model), and the spatially distributed watershed model based on SWAT (Soil and Water Assessment Tool) physical and statistical analysis. Another aim of this research is to examine changes in sea level due to climate change and to examine potential risks for coastal regions. The overall aim of this research is to:

> ***Develop GIS-based hydrological tools to support local government decision-making in a coastal flood risk management framework.***

The central research questions to be addressed in this project are as follows:

How can geospatial information and enabling technology to be used to offer the decision-support required by Victorian coastal management stakeholder groups responsible for coastal area sustainability?

This central research question is shown as five intermediate research questions and intermediate objectives in the table below.

Table 1: Intermediate objectives and guiding questions.

Intermediate Objectives	**Intermediate Research Questions**
1. To examine how geospatial information and its enabling technologies and tools are utilized in support of stakeholder decision-making in a coastal flood management framework.	RQ1. What is the current status in the integration of GIS with hydrological modelling and multi-source spatial data systems? RQ2. What is the current policy-to-practice gap in

	coastal flood-related spatial information management?
2. To analyse how a hydrology model, embedded within GIS, allows flood risks to be examined in catchments.	RQ3. How can a GIS-embedded hydrological model be used to improve the existing GIS database?
3. To investigate whether the existing database in BCSC is ready for coastal decision-making based coastal flood risk analysis of critical infrastructure	RQ4. How can the current process for drainage analysis be improved?
4. To analyse sea level rise and the risk of future coastal flooding on infrastructure	RQ5. How does a spatial decision support system help to identify infrastructure at risk from SLR flooding?

1.4 Justification for Research

The scope of this research lies within the linkage between GIS and hydrology. The aim of this research is, therefore, to summarize the rational basis for the linkage between GIS and hydrologic modelling (Grover, 1999). Its goal is to assess the type of hydrological model that is best suited to GIS.

The research will consider how advances in GIS can bring advantages to hydrological modelling. LiDAR is increasingly important as a topographical dataset. The quality and capability of DEMs mean they are of significant use to hydrological applications. LiDAR gives an extremely detailed three-dimensional outline of the land surface. The justification for the research can be summarised as:

a) Hydrological modelling is used as the basis for understanding the factors driving the development of, and requirement for, more powerful GIS-based hydrological modelling. This model is vital for the improvement of flood alerts and the establishment of targeted flood risk information to policy-makers involved in monitoring, management, planning, and decision-making.

b) Spatial information, data sharing, visualisation does not extend to coastal flooding in the GIS field. However, modelling and visualisation are very useful tools for flood risk management. While several authors provide different mapping tools and techniques for visualizing sea level rise and coastal flooding impacts (for example, see Yang, 2016; Marcy et al., 2011; Lathrop et al., 2014), these publications, different from this research in that they do not focus on data sharing.

c) Numerical flood models, as created in hydrodynamic-morphological models or a coupled-framework, need a GIS structure. There is no conventional structure to encourage interoperability with GIS frameworks. Information on likely flood impacts is required to inform land use decisions by end-users. This requires pre-disaster models that show the likely impacts.

d) Further, end-users can have improved outcomes through the ArcHydro, ArcSWAT, and screening strategies to model flood hazards. The SLR impact is also demonstrated with the model and this improves the decisions made. Future software developers can create a flexible extension in GIS. Improved flood models, science can better inform decision-makers about future coastal flooding events.

The flood models have been developed to predict coastal flooding during a storm if the coastal landscape is represented by a DEM that remains stable during the event. Four versions of the flood tool are developed in this research:

1. Using Arc Hydro tools for modelling an overland flow path, legal points of discharge (LPD) pervious and impervious surface or the possibility to identify property likely to flood before a large storm event occurring.
2. Using a SWAT creek-basin scale model to quantify the impact of flood management practices in small, complex watersheds.
3. Using extreme rainfall event development as a screening method to assess buildings and roads in flood risk areas.
4. Developing SLR flood scenarios and infrastructure risk models.

Therefore, it is suggested that integrating GIS with hydrological modelling and the structuring of coastal flood forecast data can better inform the government in its decision-making. Victoria's coastal flood risk management is limited by limitations in knowledge, making it harder for scientists and policy-makers to communicate issues such as coastal flooding (Cliquet et al., 2008). Therefore, improved information on coastal flooding risk will help support cooperation needed in coastal cities. The models developed in this research can improve the existing tools used by coastal management decision-makers.

In summary, limitations in digital spatial information adoption and decision-support for coastal flood management (CFM) policy exist. Furthermore, because coasts with hinterlands drained by perennial streams are managed by catchment authorities, a policy disconnect in CFM emerges. Accordingly, decision-support in environmental management is complex. In practical terms, some of the challenges may be attributed to failure to adopt modern spatial information maintenance, sharing and integration approaches. The study of the watersheds and coasts of the Gippsland region of Victoria provides a good example of these limitations, and this thesis explores the adoption and diffusion of digital spatial information and enabling technology integration by Victorian CFM stakeholders in this region.

1.5 Methods

The conceptual basis for this thesis involves the adoption and diffusion of decision support technology, with application to coastal zone management in Victoria. The technical basis of this thesis involves digital spatial information modelling and the integration of the data and information used in the decision-support system.

A case study approach is used in this research to gather and analyse relevant data and information. Contextual analyses look at natural wonders in their normal setting and use the information acquired by various methods and different sources (Serrao-Neumann et al., 2013). Case-based learning is used widely across many disciplines, including research pertaining to information systems operation, e.g. see (Rajabifard et al., 2002, Mohammadi, 2008, McDougall, 2006). These authors consider that a case study approach applies to the information systems field of research, as this particular field is characterized by constant change and innovation. Yin (2003) considers that case study research methods can be used when the

phenomenon under study is not different from its context, for example, the complex interactions between advanced technologies and organizations. Accordingly, case study research methods can be applied when ‘‘how and why’ questions are asked, when the focus is on the contemporary phenomenon within some real-life context and when the investigator has little control over events. Yin (2003) considers contextual analyses appropriate when examiners either want, or are forced by circumstances, to define research topics broadly and not narrowly, to cover contextual or complex multivariate conditions, and not simply disengaged factors.

Further, Yin (2003) considers that should case studies refer to a new innovation such as digital spatial information and enabling knowledge, opinions of the technology used are essential and invaluable aids for understanding the actual uses of the technology and/or potential difficulties being faced by adopters. For this research, the author/researcher was an employee within the BCSC, allowed an augmented level of direct observation, e.g. see Yin (2003) of the dynamics surrounding organisational behaviour of the stakeholders towards enabling technology and geospatial data.

The research design (refer Figure 1-1) for this project draws together a framework for information systems case study research approaches as outlined by Kaplan and Duchon (1988), Lee and Heaney (2003), Onsrud et al. (1992) and Yin (2003). Stage one of the research design comprises detailed project formulation, including a review of the relevant theory and practice. This provides the basis for the improvement of an appropriate theoretical framework for data collection and evaluation. Data and information collection using mixed research methods is used in Stage Two. Data and information obtained via this stage then informed Stage Three of the research, being the development of a suite of CFM stakeholder needs-focussed geospatial tools for application within the Victorian CFM program (which could be adapted to other national and/or world-wide CFM programs). Research outputs from Stages 1-3 combine to form Stage Four, which involves the conclusions and recommendations section of this thesis.

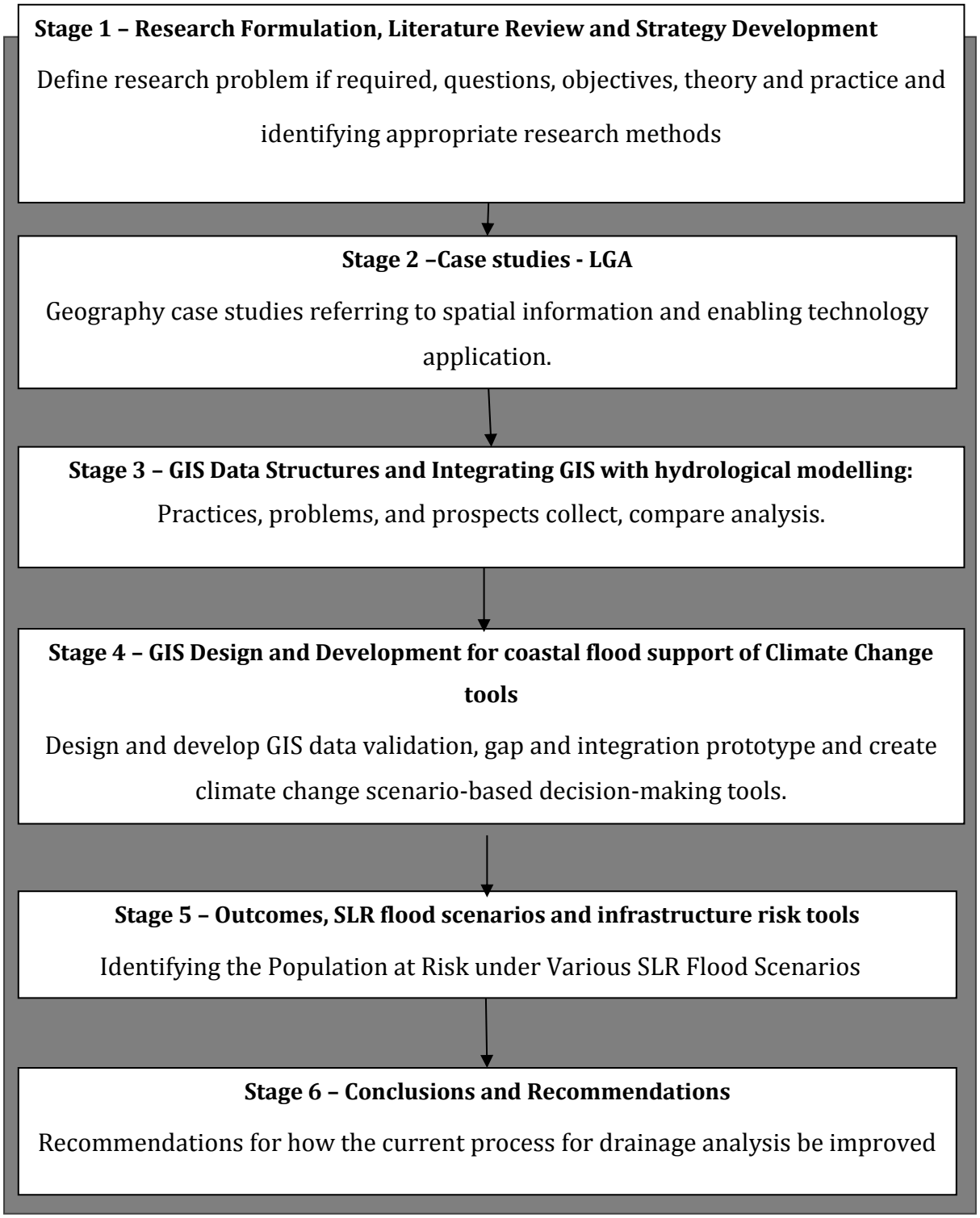


Figure 1-1 Proposed research design

The research in stages one to three will be synthesized and analyzed to form the conclusions and recommendations of this research. Information from the first two stages includes the usage

of a GIS embedded hydrological model, to improve administrative practices informed by coastal flood hazard modelling. It included a literature review concentrated on coastal floodplain management in the Victoria setting, the user needs of spatial analysis and the concept of hydrological modelling using LiDAR are also included. In Stage 3 and 4 the discussion involves:

- GIS functionalities in hydrological modelling and LiDAR data implementation for the Victorian Coastal Council's flood model,
- The importance of the spatial database for 'on-request' hydrological modelling
- Coastal flood modelling through an examination of GIS datasets to decide the gaps in spatial information and the essential characteristics
- Spatial and hydrology models for coastal flood risk management due to global SLR.

Stage one and two data focus on flooding and floodplain management in the Australian setting. Users need spatial investigation and a reasonable hydrological visualisation utilizing LiDAR. Stage 3 and 4 examine GIS functionalities in hydrological and LiDAR applications to show the effects along the Victorian coast. They examine the importance of GIS database for 'on-request' hydrological examination and coastal flood modelling over the use of spatial datasets to decide the gaps in GIS information and the required characteristics of hydrology models for modelling SLR.

The outcomes from this stage will address the central research and objectives problem. In these terms, the knowledge gained from this project can inform future CFM and provide spatial information infrastructure (SII) policy reforms in Victoria. This may be bridged by the previously mentioned policy-to-practice gaps related to the integration of spatial decision-support for CFM in Victoria. Given that the 'centralized SDI' approach to decision-support has been widely adopted in many other countries and Australia, the research findings are also relevant to the Victorian and Marine Coastal Act 2018 which mentions Marine Spatial Planning (MSP) under "Strengthening Marine Management". This Act supports protection of the coastline and addresses the challenges of natural hazard, population growth and ageing infrastructure, and requires that partners work together (VMCA, 2018).

1.6 Thesis Structure and Outline

The thesis is organized into six stages as illustrated in Figure 1.1 and as shown in Figure 1.2 below.

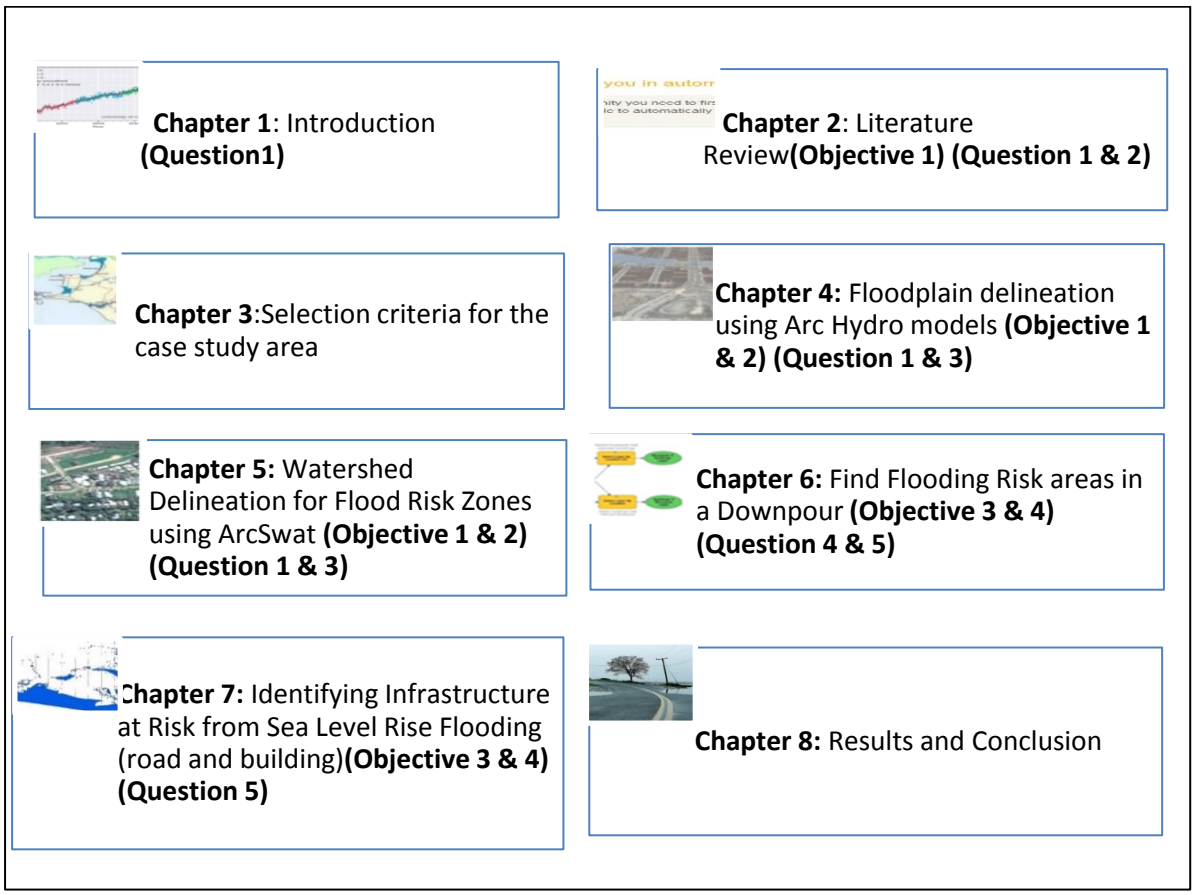


Figure 1-2: Structure of the thesis in relation to the objectives and research questions.

The first stage involves Research Formulation, Literature Review and Strategy Development. Chapter 1 provides the introduction and theoretical framework, describes the research problem, research aim, and research questions. The literature review on coastal flooding, flood management, GIS and Hydrological modelling is contained in Chapter 2. This chapter, answers research question 1 and 2.

Stage 2 is the Case studies and the pilot study area is described in Chapter 3: Pilot study area: Bass Coast Shire Council (BCSC). Chapter 3 introduces the standards for choosing the pilot study area—the BCSC and it is coastal hydrological and associated qualities.

Stage 3 focuses on GIS data structures and processes for integrating GIS with hydrological modelling. Chapter 4 provides a case study focusing on floodplain delineation using Arc Hydro models, the choice of methods and user data information needs in the context of local coastal flood-risk analysis. It contains the depiction of the strategies and result of spatial information linking for extricating overland flow through the property and reduce the risk of flash flooding area utilizing GIS-embedded hydrological models. The author also discusses the limitation in existing local coastal flood relevant spatial databases. This chapter answers research question 1 and 3. Chapter 5 then involves a case study on the watershed delineation of flood risk zones using ArcSwat. In Chapter 5 the numerical models can simulate hydrological processes using ArcSWAT. This Chapter answers research question 1 and 3.

Stage 4 involves GIS design and development for coastal flood support of climate change tools. The results of this stage are found in Chapter 6 which is a case study on finding areas at risk of flooding in a downpour. Chapter 6 uses the DEM dataset in GIS-embedded hydrological modelling. This Chapter answers research question 4 and 5.

Stage 5 involves the outcomes, SLR flood scenarios and infrastructure risk tools. Chapter 7 involves a case study which develops an approach for identifying infrastructure at risk from SLR flooding. Chapter 7 investigates LiDAR modelling of coastal inundation under future SLR and describes the current and future "risk to infrastructure. This Chapter answers research question 5.

The final stage involves conclusions and recommendations. The result of this stage is contained in Chapter 8 which is the synthesis of findings and includes the conclusions and recommendations for future research for improving Victoria's coastal flood management. Chapter 8 presents the results and conclusions of the research and provides suggestions for future research. In this concluding Chapter, the problem and primary research objectives are addressed and ways for future research are suggested.

1.7 Key Assumptions and Scope

There are limitations in how the "spatial industry" (Douglas et al., 2008) can support the implementation of the climate change policies and practice outlined in the Victorian Coastal Strategy. The existing flood models were developed to predict the coastal areas that may be flooded during storms assuming that the coastal landscape is represented by a DEM that is stable during the event. Results presented in Chapters 4, 5, 6 and 7 highlight different flood tools developed for coastal areas assessing the impact on coastline degradation infrastructure. As discussed in the literature review, there has been limited research on modelling the impacts to infrastructure and the research in Chapter 4, 5, 6 and 7 is therefore novel.

While it is acknowledged that a portion of the catchment was used, the area covered in the analysis in this thesis was not affected, particularly in the coastal zone. However, the important aspect that has been established in the research is the procedure that has been developed, one that can be applied to any coastal zone.

1.8 Chapter Summary

Chapter 1 has established the research justification, aim, goals, objectives and synopsis structure of the thesis as a foundation for the Chapters that follow. Later Chapters build on this framework. The next Chapter provides a literature review of the role of GIS, hydrology and information models. Later Chapters build on this literature review by describing the case study area and the results of the research, before responding to the intermediate research questions posed in Chapter 1.

Chapter 2

2 Literature Review

2.1 Introduction

Floods brought about by high levels of precipitation, storms or deficient drainage systems can result in damage to infrastructure, loss of life, property damage, individual hardship and economic loss. For Australia, floods are the most costly natural disaster (Barnett et al., 2010). Major floods can cause damage that runs into hundreds of millions of dollars. Household exposure to floods is predicted to get worse because of climate change and population growth, especially in coastal areas. Therefore, it is of importance to better understand coastal flood management (CFM), which is the focus of this Chapter. This Chapter provides background information about coastal flooding and its impacts on communities and the environment in Victoria. The second section discusses the issues caused by coastal flooding and the flood-risk design strategies used by the three levels of government in Australia. Thirdly, it gives an overview of CFM stakeholders' responsibilities in flood-risk areas. They can identify high priority areas at risk of flooding through the context of CFM in Victoria. Finally, geographical information systems (Petroselli and sensing, 2012) embedded in hydrological modelling are used to identify risk areas.

2.2 Background

Many Victorians live near to the coast. Four out of five Victorians visit the coast every year and they enjoy a wide variety of recreational hobbies. There were an estimated 9.2 million international visitors to Australia in 2018 and the coast is the destination for an increasing domestic, national and international tourist marketplace. Tourism Victoria, working closely with Tourism Australia, launched its $40 million global campaign. In 2015–16, tourism along the Mornington Peninsula and the Great Ocean Road generated approximately $795 million and $700 million for Victoria's economy respectively. Built and natural assets along the coast can provide valuable protection for other coastal assets such as boat ramps, coastal parks, stairs, jetties, and viewing platforms, which provide vital economic, recreational, environmental services and roles. The National Climate Change Adaptation Research Facility (NCCARF) in 2011 evaluated the economic value of Victoria's coastal resources, including natural and built assets at $18.3 billion every year. In 2013, the Victorian Coastal Council (VCC) evaluated

that it would cost $24–$56 million annually to substitute the natural safety provided by coastal property like beaches and dunes. However, some of the infrastructures along the coast are at risk of climate-related impacts, including drainage and sewerage networks, roads, telecommunications, and housing.

Floodplains and associated wetlands support the flow of water by providing normal stockpiling areas where floodwaters can be held and gradually discharged as the streamflow reduces. Floodplains disperse the intensity of floodwater thereby reducing the damage that they can cause. Nutrients, debris and sediments are filtered, leading to an improvement in the health and quality of waterways and a boost in floodplain productivity. As a result, floodwaters hold and renew wetlands and bolster the widely varied vegetation of floodplains and waterway frameworks. Most of the impacts of flooding occur when urban development encroaches upon the floodplain and does not protect natural drainage lines and overland flow paths. For instance, in 2005 flooding compromised around 20,000 assets, with stormwater drains overflowing, causing flash flooding affecting 82,000 properties (Melbourne Water, 2007a) in the Melbourne metropolitan area. In Australia between 1967 and 1999, riverine flooding was the most damaging type of natural disaster accounting for $245 million AUD as shown in Figure 2-1.

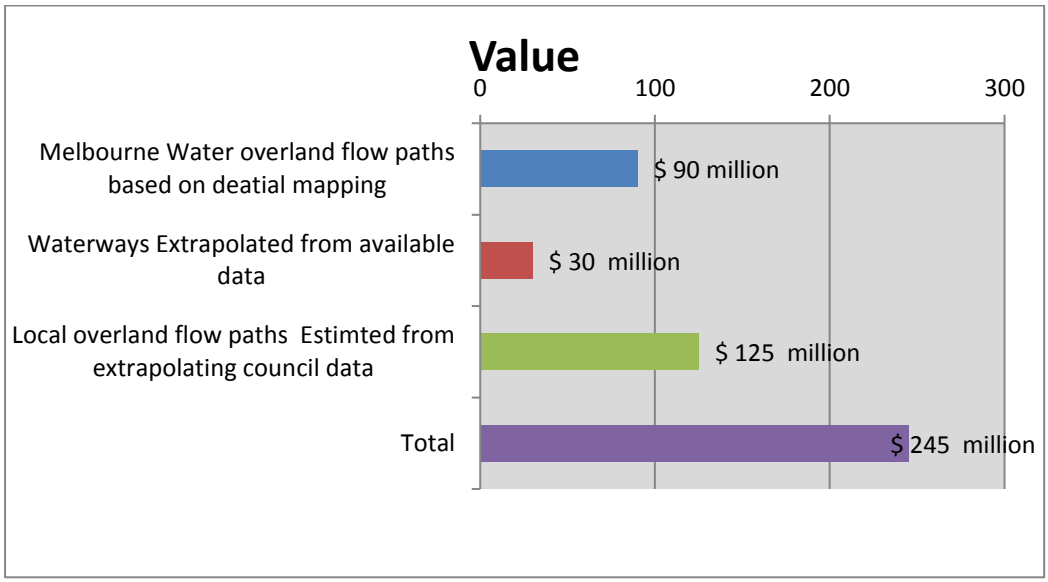


Figure 2-1 Annual Average Damage in Melbourne, 1967-1999 (Water, 2007)

Annual Average Damage for the region ($ Millions)

The Annual Exceedance Probability (AEP) is the probability of a surge of a given size in any one year, normally communicated as a rate. The Average Recurrence Interval (ARI) is a measurable gauge of the normal time frame in years between the events of a surge of a given size. For example, a flood larger than the 100-year ARI flood event will occur on average once every 100 years. The ARI does not indicate when a surge of that size will happen, but instead, the likelihood of it occurring. The multiyear ARI, or 1% AEP flood, is the typical value on which decisions about proposed urban improvement are based. Precipitation events can fluctuate in span and force. A storm of a specific length and force will have diverse impacts in various zones. Thus, there is no single 1% AEP storm event for Melbourne, but instead a progression of events as illustrated by the curve shown in Figure 2-2.

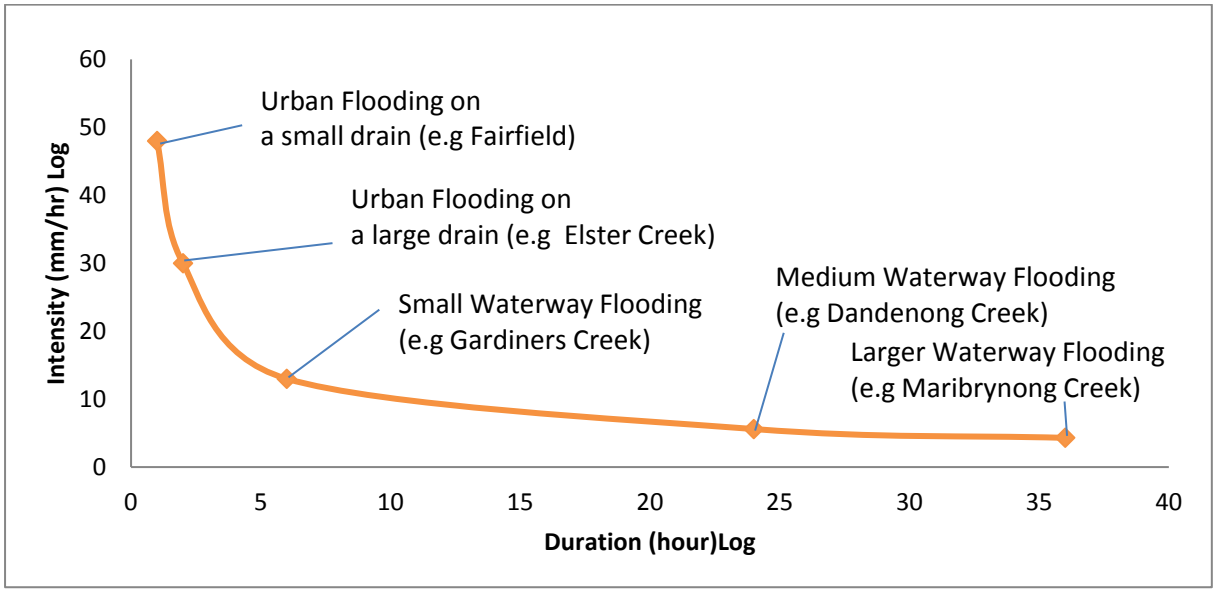


Figure 2-2: Hundred-year storms in Victoria, 2001 -2050 (Water, 2007).

The orange line represents a series of rainfall events (known as an intensity Frequency Duration Curve) that illustrate the duration and intensity of hundred years storms for a range of catchment sizes.

Most flooding in the region is brought about by precipitation, either as riverine flooding or overland streams (Weldon et al., 2014). Other types of flooding include coastal tidal floods, storm floods and tidal waves. These are not now considered as a critical risk. Riverine flooding is caused when the runoff from significant storms surpasses the channel limit of a stream or brook and floods onto the encompassing flood plain. Overland streams, or floods, happen when

runoff from serious storms surpasses the limit of the underground drainage network. At the point when streams surpass the limit of the underground framework, water starts to stream downhill over the land along with regular streamflow over valleys towards the closest brook or waterway.

Melbourne Water has identified around 82,000 assets that are at risk of flooding from overland streams with roughly 37,000 assets being exposed to flooding above floor level from overland streams. Coastline tidal flooding, storm floods and, ocean tides can influence typical sea levels causing dangerous flooding along the coastline and lower reaches of tidal waterways, particularly when accompanied by high precipitation. However, the tidal impacts along an estuary or waterway lessen with distance from the coast.

Storm-driven floods are another influence on water levels along coastal regions and occur through a mixture of low barometric pressure, solid breezes and heavy waves. Fortunately, extraordinary precipitation and storm-driven floods seldom occur. Flooding occurs most commonly from heavy rainfall when natural channels do not have the capacity to carry extra water. To comprehend the potential expense of flooding in any year, the impact caused by all floods over a period is isolated by the number of years in that period. This is called the Annual Average Damage (AAD) and is illustrated in Figure 2-1. The flood damage curve appearing in Figure 2-2 to give an estimation of the likely harm in any given year.

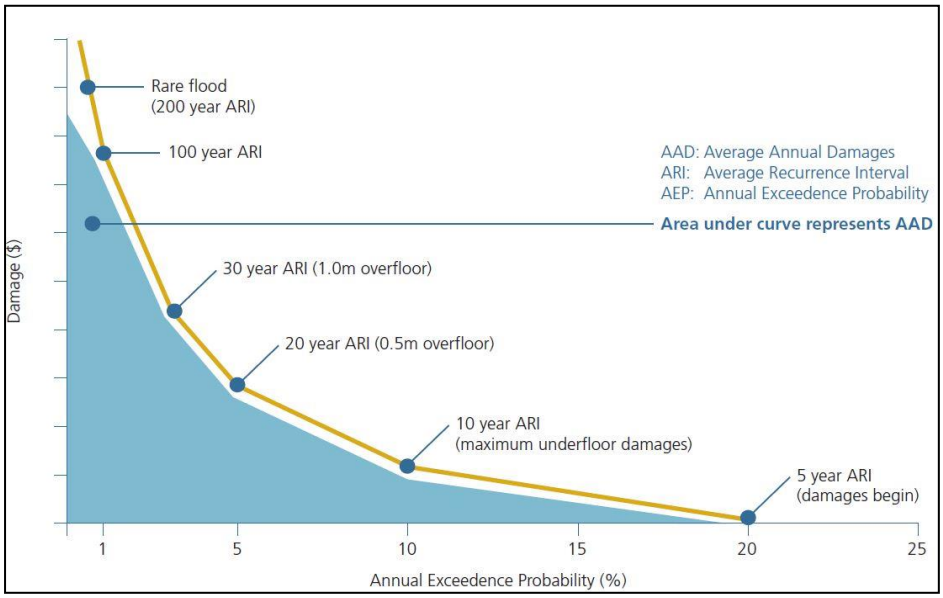


Figure 2-3: flood damage curve, The Port Phillip and Westernport Region, 2007 (Water, 2007)

In 2018, global mean sea level was 3 inches (77 millimeters) above the 1993 average (Lough and Hobday, 2011), for the most part, because of warming of the oceans with a contribution from the loss of land ice (Thom et al. 2005, Gregory and Huybrechts 2006). Australia started observing sea levels around the mid-1990s, making it difficult to derive critical patterns because of the brief period. Water levels have expanded around Australian in line with worldwide trends (Church and White, 2006, Hoegh-Guldberg, 1999). Rates of SLR indicate local variability, especially along with the western and northern coasts and along the central-eastern coast (Li et al., 2005). The variation in sea levels is related to yearly atmospheric variation, for example, attributable to ENSO, modifications in the quality of the East Australia Current (EAC), and environmental flow elements (Lough and Hobday, 2011). SLR has contributed to the recurrence and force of ocean wave events in Australia and abroad (Keenan et al., 2011). The rate of extraordinary ocean wave events in the last half of the twentieth century has been many more times the previous half (Church and White, 2006).

2.3 The Concept of Coastal Flooding

A coastal flood occurs in areas that lie on the coast and are overflowed by the ocean during storms. The strong winds of the storm push the water towards the coast and create relentless waves. A storm is formed in a low-pressure area, and beneath a low-pressure area, the sea level is higher. A flood begins when waves move inland on an undefended coast or break the coastal

barriers (for example, hills, seawalls and dams). In sandy drifts, each wave in a storm will remove sand and over time, a ridge may collapse. One characteristic of a coastal flood is that the water level falls and rises with the tide. At high tide, the water may flow in and at low tide, it may recede again. At the point when ocean barriers are ruptured, low tide provides an opportunity to fix the damaged barriers.

Victorian's coastal areas are extensively affected by human action. Nonetheless, Australia's response has been poor as evidenced through various inquiries and state of the environment reporting (Deegan and Gordon, 1996). These issues and difficulties are examined in this thesis against the logical foundation of coastal management and planning. Contemporary strategies for CFM incorporate management standards, value issues, biodiversity protection and the requirement for a precautionary approach. However, the challenges for coastal management are experienced at all levels (Arnold et al., 2012). According to modelling by (Nicholls et al., 1999), tens of thousands of homes and organizations in Melbourne are predicted to face a greater risk of tidal flooding by the end of the century, and major roads, tram routes and industrial areas could disappear under water due to future SLR. Strom surges can produce much higher sea levels than the normal high tide, with consequent coastal and inland flooding.

2.4 Issues Arising Coastal Flooding

Future climate change is likely to increase the impact on populations at risk along the coast. Victorian coastal zones face risks related to fire, flood and storms. However, the convergences of risks along the coast due to climate change and urban development, mean that more of the population will be exposed (Council, 2008). The Victorian Coastal Strategy (2014) recognized adaptation to climate change is one of the key issues facing the coastal areas, which is reflected in the legislation setting up that policy—the Coastal Management Act 1995. According to the Marine and Coastal Act Consultation Paper of August 2016, the coastal planning framework aims to guide where future planning might be needed and resolve the disputes in the marine estate.

Coastal spatial planning involves ecosystem-based management of coastal waters by all the stakeholders, for a range of uses according to the ecological, economic and social requirements. The Marine and Coastal Council (Trkman and McCormack) identified five main issues confronting our coast that require particular consideration (DELWP, December 2017):

1. Managing population growth,
2. Adapting to a changing climate,
3. Managing coastal land and infrastructure,
4. Valuing the natural environment, and
5. Integrating marine planning

2.4.1 **Sea Level Rise**

Eighty-five per cent of Australians live within 50 kilometres of the coast and at risk of being impacted by the estimated SLR predicted by 2100 (Wang and McAllister, 2011). Globally, the mean sea level has risen by 20 cm since the end of the nineteenth century (Lough and Hobday, 2011), as illustrated in Figure 2-4. For the most part, this is because of the warming of the seas and melting ice (Thom et al., 2005). SLR is currently moving toward the highest predictions by the Intergovernmental Panel on Climate Change (Keenan et al., 2011). Sea level monitoring around the Australian coast started in the mid-1990s, making it difficult to predict critical patterns because of the short monitoring period. While sea levels have risen around Australia in accordance with worldwide patterns (Hoegh-Guldberg, 1999, Church and White, 2006), there are local variations, being higher along the west and north coast and lower along the east-coast Lai et al. (2005). Changes in SLR are related to yearly atmospheric pressure changes, for example, due to El-Nino, changes in the quality of the East Australian Current (EAC) and atmospheric pressure (Lough and Hobday, 2011).

Water levels increased the frequency and power of large ocean waves in Australia and abroad (Keenan et al., 2011). The rate of extraordinary ocean wave events has increased in the second half of the twentieth century (Church and White, 2006). SLR is estimated to rise in the coming decades from 280 to 340 mm by the 21st century (compared to 1990).

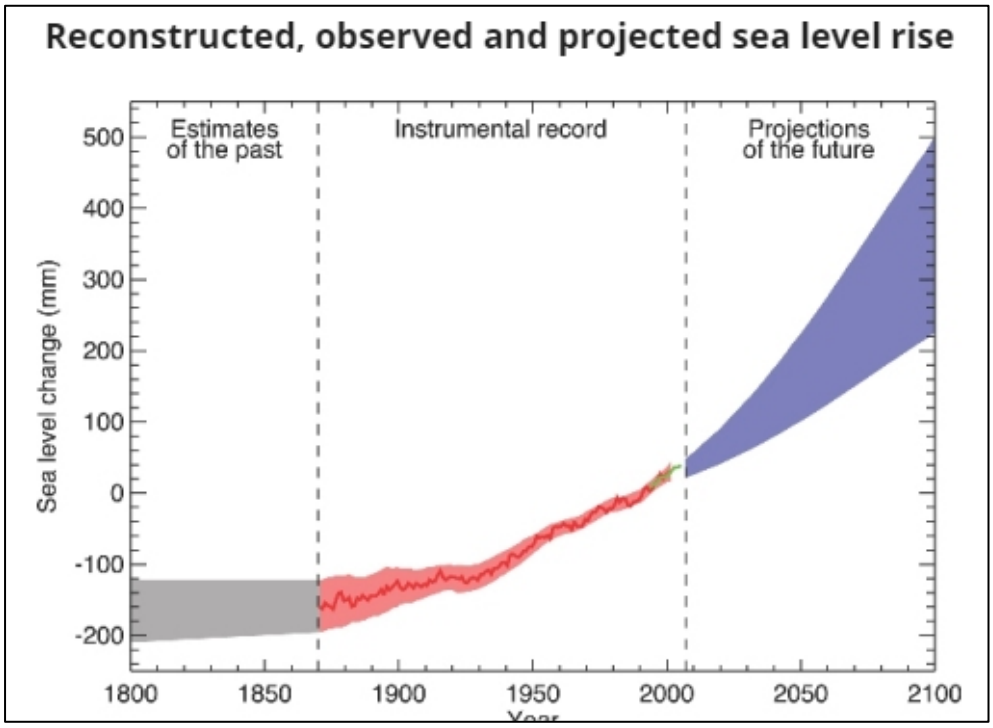


Figure 2-2: Reconstructed observed and projected SLR

(Source: Parliament of Australia, 2018).

The Intergovernmental Panel on Climate Change (IPCC, 2007) provided SLR projections ranging from 0.18 to 0.59 m by the end of the 21st Century. These numbers did not, however, include any allowance for possible increases in the melting rates of the Greenland and West Antarctic ice sheets. It has been estimated that increased melting of these ice sheets could add 0.1 to 0.2 m to the upper bound of SLR from 2090 to 2099. Further, the work of Rahmstorf et al. (2007) found that the rates of SLR measured by tide gauges and satellite altimeters were tracking near the upper bounds of the IPCC, SLR projections.

In response to the above SLR projections, the Victorian Coastal Strategy (Council, 2008) recommended that "a policy of planning for SLR of not less than 0.8m by 2100 should be implemented." The strategy further recommended that "this policy should be generally applied for planning and risk management purposes" and the strategy is to be refined "as new scientific data become available."

In their assessment, they reviewed several post-IPCC (2007) projections of SLR. These included estimates of SLR by 2100 of 0.82 m by Hunter (2010) of 1.10 m by the Netherlands Delta Committee (Vellinga et al., 2008) and an upper limit of 1.40 m by Rahmstorf (2007).

The current SLR projections for Australia are provided by CSIRO (Church and White, 2011). These projections are based on the range of climate change scenarios considered by IPCC (2007), as reproduced in Church et al. (2011). The projections include outer ranges for all scenarios with an additional allowance for increased melting of the Greenland and West Antarctic ice sheets. The upper limit for the increased ice sheet melting scenarios is for SLR of about 0.82m by 2100. This is consistent with the value given by Hunter et al. (2010). It also provides an upper limit for SLR of about 0.2m by 2040. The three scenarios created by CSIRO for SLR between 2030 – 2100 (with respect to 1990 levels) are displayed in table 2.1. The minimal rise scenario (B1) envisages a global pattern of decreases in worldwide changes at the upper end of predicted SLR by 2100. The medium-rise scenario (A1FI) reflects the upper end of IPCC's Fourth Assessment Report (IPCC AR4) were based on recent global emissions and observations of SLR. The last scenario (high end) considers the upper bound of the AR4 predictions and it is consistent with post-IPCC AR4 examinations.

Table 2.1: Three worldwide sea-level rise scenarios, 2030-2100 (metres), Source: (Hall et al., 2006)

Year	Scenario 1 (B1)	Scenario 2 (A1FI)	Scenario 3 (High end)
2030	0.13	0.15	0.2
2070	0.3	0.5	0.7
2100	0.5	0.8	1.1

LiDAR height information gives clear advantages in outlining lands subject to inundation related to a specific SLR. LiDAR elevation information has been effectively utilized in the past for flood modelling in low relief areas (Bales *et al*., 2007; Sanders, 2007), and it is appropriate for improved categorization of coastal lands vulnerable against potential inundation from rising oceans. This research incorporates an evaluation of the vertical accuracy of different DEM

datasets that have been utilized to show potential lowland flood impacts and how LiDAR information provides increased precision in defining vulnerable coastal lands.

The Land Subject to Inundation Overlay (LSIO) proposed by Planning Scheme Amendment C82 was based on the Victorian coastal inundation dataset that was developed as part of the Victorian Government's Future Coasts program. The purpose of this data set was to provide a consistent state-wide assessment of the potential physical impacts of SLR associated with climate change. The objective was to provide information that assists in the identification and communication of coastal inundation risks at the catchment and regional scales across Victoria. The Future Coasts LiDAR Program has used a three-stage process to identify land that will be affected by coastal inundation because of SLR (Pittman et al., 2013).

2.4.2 Managing Risks to Coastal Flood Assets

Approaches to mitigating natural hazards (Hallegatte et al., 2013) defines coastal hazards as natural coastal processes, such as currents, tides, winds significantly increasing impacts on coastal assets, as outlined in Figure 2-4. According to Baby et al (2012), the West Gippsland CMA produced small-scale maps of the existing flood risk (as affected by storm surge) and maps of the impact of a 0.2 metre SLR – projected to occur by 2030 - and a 0.8 metre rise for 2100, which were used in the Victorian Coastal Strategy 2008.

the National Climate Change Adaptation Research Facility (NCCARF) heavy rain, strong wind, large storm surges, are likely to have an adverse effect on life, assets or aspects of the human and natural environment. From coastal hazards, coastal assets are at increasing risk including inundation and erosion. The risk will be worse and accelerated due to climate change by in 2011, NCCARF estimated that Victoria SLR will by 0.8 metres by 2100, significantly increasing impacts on coastal assets, as outlined in the table below.

Table 2.2: Flood risk activities based on an SLR of 0.8 meters by 2100

Asset	Quantity	Value
Built Assets		
Residential Buildings	31000-48000	$ 6.5 to 10.3 billion
Commercial Buildings	up to 2000	$12 million
Roads	257 km	$9.8 million
Railways	125 km	$500 million
Government-owned public facilities	87	Not known
Maritime Assets	Not known	$220 million
Coastal protection structure	Over 1000	$700 million
Natural Assets		
Public land	586 km	Not known
National and state coastal parks	15	Not known
Vegetation	48720 hectares supporting 95 ecological vegetation classes	Not known
Mangroves	6300 hectares	Not known
Wildlife reserves	14	Not known
Natural conservation reserves	9	Not known
Flora and fauna reserves	4	Not known
Rare or threatened species	880	Not known

Source: Built asset data (NCCARF, 2011) and 2016 PV data. Natural asset Figures (DSE, 2012), Teeling et al. (2005) data, 2013 VCC data and 2016 Victorian National Parks Association data. Note: This table excludes costs related to effects on oceanic resources and loss of income for different exercises that depend on coastal resources.

Effective Asset Risk management is an important part of risk management. In coastal areas, risk assessment is used to identify priorities and manage risks that may affect high-value assets, including the risk of erosion. In 2016 Victorian Government Risk Management Framework requires organizations to apply ISO 31000 to their asset management practices. The Victorian Coastal Hazard Guide is produced by DES (2012) based on ISO 31000. The DELWP's 2015 Management Accountability and Good Practice Guidelines state that CoMs should have a risk management process in place to manage specific risks identified in their area of management. There are risks to assets. The CoMs must review this assessment annually to determine if any changes have been made to identify new risks or influence the rating of existing risks. The process used in the CoMs and the decisions taken in the risk management plans should be documented. It is important to have a strong, risk-based asset management approach to target limited funds to high-value assets at the highest risk for coastal asset management. Audited

firms have adopted unmanageable risk assessment approaches, and as a result, it is unclear whether coastal expenditures lead to high-value, high-risk assets.

2.4.3 **Land Use Planning**

The state planning system includes various planning policies and tools that are relevant to the protection of coastal resources in the face of SLR, which were introduced in planning schemes in 2008 and 2012. These planning controls serve as protection for future coastal resources. In relation to coastal land use and development, they also guide decision-makers and coastal stakeholders on how SLR will impact their planning decisions.

Bass Coast Shire Council are one of only three coastal councils to apply the '*Land subject to inundation*' overlays across coastal land within their municipalities identified as subject to coastal water inundation. Bass Coast initially did this using state-wide coastal flood data and then updated it when Local Coastal Hazard Assessment (LCHA) information was available.

The Mornington Peninsula Shire Council (MPSC) plans to revise their scheme to apply '*Land Subject to Inundation Overlay (LSIO)*' across the areas at risk of coastal flooding in the Western Port areas of the municipality. Other councils do not use separate overlays, which do not require specific coastal hazard considerations. Some councils contacted during the test and the audit conducted that information on local assessment of coastal risk (LCHA) was not specific enough to determine the extent of the overlap, although the MPSC, South Gippsland Shire Council, Bass Coast and Moyne's have been able to do this. However, it is difficult for planners to use coastal risk information such as LSIO as a key factor in their decision-making decision when approving a planning application. The councils that were consulted also noted difficulties in translating and implementing coastal planning policies and SLR benchmarks into land use and development decisions (based on feedback from 3 council planning and engineering staff from Bass, Moyne, and South Gippsland Councils).

2.4.4 Focus for Future Action

The Climate Change Act 2017 is committed to ensuring the Victorian Government, the government's decisions, policies, programs and processes appropriately address climate change challenges. Government departments and agencies also need to do this when making decisions under the law. The Climate Change Adaptation Plan 2017-2020, created under the Emerging Climate Change Act 2010, recognizes a shared responsibility but does not assign any minister, department or agency the responsibility for developing and implementing this plan, although it does not act individually. The Minister of Energy, Climate Change and Environment is responsible for reporting on the implementation and effectiveness of each plan. The Climate Change Act of 2017 provides a mechanism for strengthening accountability for the delivery of adaptation activities. Ministers who align responsibilities with their portfolio may be designated to prepare adaptation action plans under the new climate change strategy, which will replace the adaptation plan from 2020. They must report on their application and efficiency. Given the gradual progress on climate change adaptation, state and local governments, public sector agencies need to take the necessary training, research, and necessary steps to address the challenges that present leadership adaptation.

2.4.5 Population and Growth and Coastal Development

Victoria is facing extraordinary population growth along the coast (Table 2.3). This dramatic population growth along with increasing numbers of tourists in coastal areas is pressuring many of Victoria's coastal environments and communities (Council, 2008). Every year the population of coastal towns fluctuates throughout the year.

Table 2.3: Summary of historical and projected population changes in Coastal Victoria.(Council, 2008).

Population				**Actual Change 1996-2006**		**Projected Change 2006-2016**	
Area	**1996**	**2006**	**2016**	**NET**	**%**	**NET**	**%**
Coastal Victoria	883698	1017654	1109889	133956	15,16%	92235	9.06%
Coastal Shire	19.38%	19.84%	19,91%	-	-	-	-
Victoria	4506149	5128300	5574755	568151	12.46%	446455	8.71%

Figure 2-5 illustrates the relationship between population change and distance from the coast. The significant modification in land use 30 kilometres inside the coast has changed from rural and peri-urban to urban land (Figure 2-6).

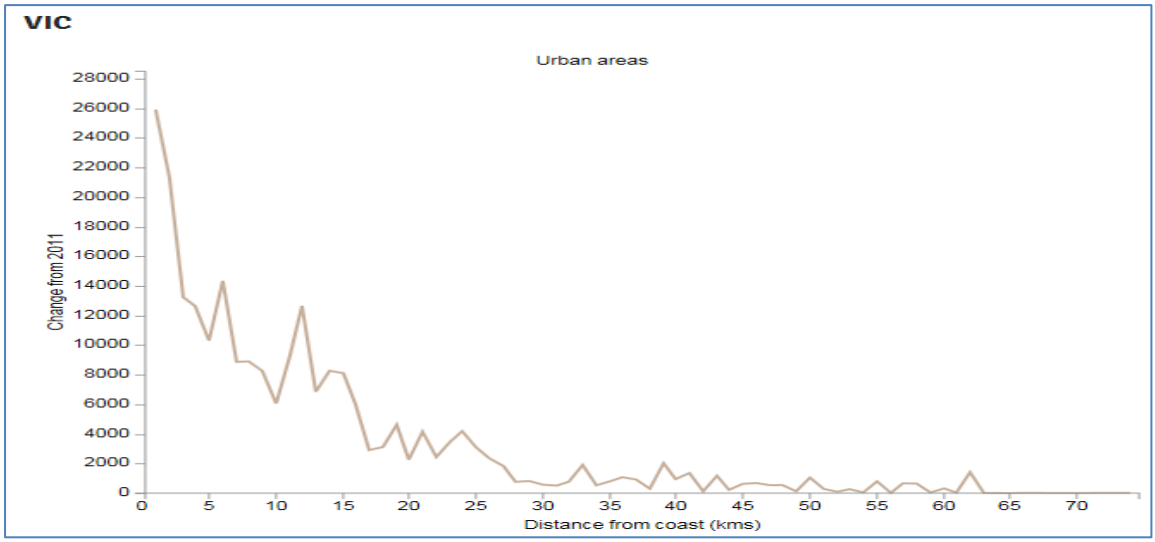


Figure 2-3: Australian environmental state, 2016, Urban development and Population growth: coastal development and land use. Source: (Cresswell and Murphy, 2017)

Growing wealth and prosperity and more accessible technology and infrastructure, including improved transport networks, are a major contribution to coastal development. These factors are drivers for mobility choice when considering where to visit and live. The "sea change" choice brings numerous advantages, for example, more dynamic communities and improved local economies, improvements to infrastructure and greater local government capacity. However, development in coastal areas can also impact biodiversity, affect water quality, damage wetlands, cause degradation, and impact biological systems. Coastal urbanization can place a greater load on existing infrastructure such as stormwater, water supply, waste and streets, drainage. It also has consequences for local government, for example, during bushfire, storms, and flooding (Council, 2008).

2.4.6 **Marine Ecological Integrity**

Victoria has a distinctive marine environment where many unique species live. These marine ecosystems are native to Australia (Victoria Coastal Council, 2014, Marine Ecological Integrity). However, as much of Victoria's marine plants and animals are small and some are

hidden under the sea, the biodiversity is not well understood and appreciated (Hurlimann et al., 2014). Victoria's marine environment supports tourism, shipping, fishing, aquaculture and recreation. These uses can be influenced by actions that impact ecological integrity of the coast, putting marine ecosystems at risk. The risks include loss of endangered species, unsustainable land use affecting species and physical changes to natural surroundings which varies along the coast. These risks to marine biodiversity are not known and can be inconspicuous. Likewise, the risks can be confusing, synergistic and hard to foresee. The decision-support system developed in this research will address the issue of marine biological integrity by:

- Improving information available for management of the ecosystem by modelling flooding and likely impacts.
- Improving decisions on the location of urban development and infrastructure.

2.4.7 Coastal Erosion and Recession

Coastal erosion and recession (progressive erosion) are mainly caused by waves, storm surges and high tides. This can result in a coastline retreat, depending on the shoreline type. The recurrence and amount of coastal degradation and subsidence are caused by incremental rising sea levels. With SLR, more frequent storms will most likely drive erosive waves higher on the shoreline. Coastal barriers (e.g. landform types, silt supply and topographical features) that encourage subsidence influence the form of the coastline or shoreline at any time.

Potential effects of SLR on settlements and infrastructure:

The Australian coast is impacted by various natural hazards, including bushfires and tidal waves. The coastal impacts include degradation and storm tide inundation. Storm events, and East Coast Lows produce incredible waves and winds which lead to degradation and tide inundation that can harm settlements and their foundations. SLR projections demonstrate that environmental change will expose more settlements and their infrastructure to these hazards. Figure 2-6 demonstrates the effects the Victorian Lakes Entrance coastal area principally dependent on a 1 meter SLR (very high greenhouse gas state of affairs in 2100). The degradation of local hills and coastlines create coastal regions that are more susceptible to damage by:

- Reducing the natural barriers, increasing the exposure of the settlement to floods.

- Directly undermining the structures, risking the collapse of the footings or exposure to wave action.

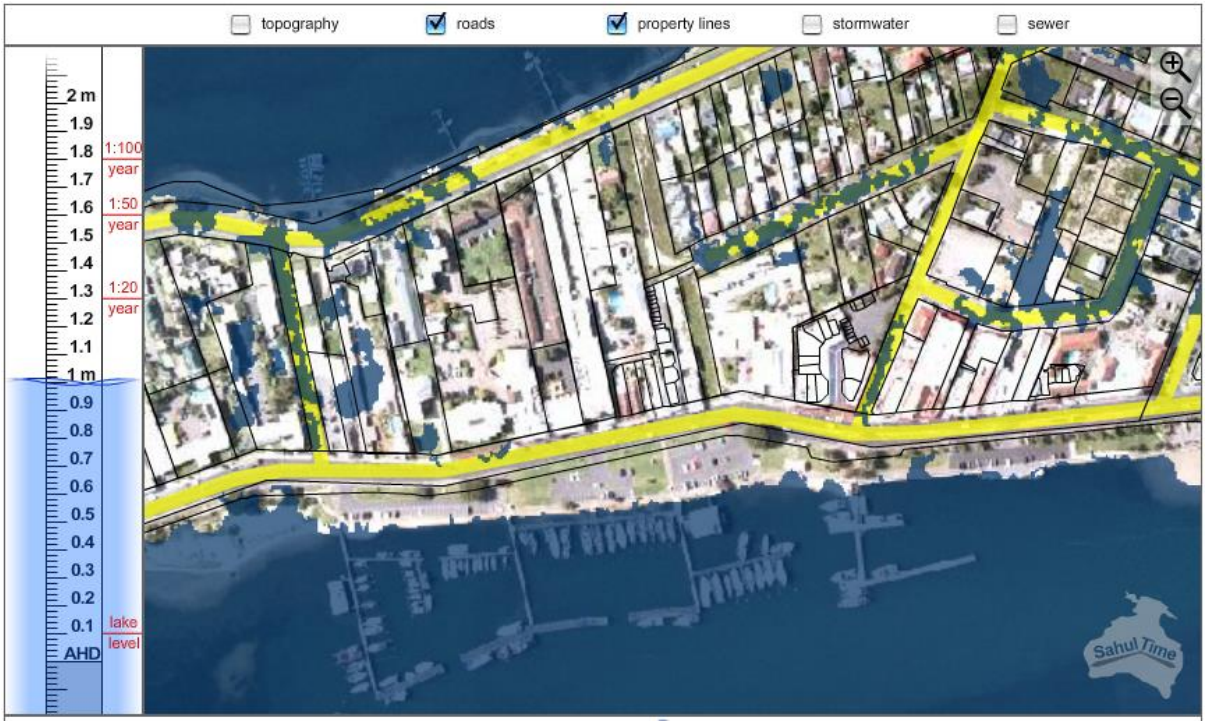


Figure 2-4: Flood at Lakes Entrance for 0.0 m AHD (bottom), 1.0 m AHD (middle), and 2.0 m AHD (top) (Wheeler, 2010).

2.5 Coastal Governance in Australia

The recent decade has seen an increased focus on the management of the world's oceans and seas. Australia has various laws and approaches to manage coastal areas, with responsibility shared between the Commonwealth government, Australian states and territories, and local governments. Commonwealth jurisdiction is from state waters to the 220 nautical-mile limits off the coast and is called the Exclusive Economic Zone, while state waters are from the territorial sea baseline to three nautical miles from the coast. However, the Commonwealth has considerable financial powers and can provide a leadership role through the setting of national policy and standards. State and territory agencies have responsibility for the management of coastal land within their jurisdiction, and local governments undertake many of the maintenance tasks and development control of the coastal area.

2.6 Victorian Coastal Flood Risk Management

The Victorian Floodplain Management Strategy (DELWP, 2016) was released in April 2016 outlines the accountabilities for coastal flood risk management regarding sharing coastal flood risk data, evaluating explicit coastal hazards, mapping waterfront inundation at various scales, land use arrangements and coastal flooding. The strategy provides for assessing Victoria's coastal flood risk and:

- Developing the standards and identifying priorities for undertaking coastal hazard duties.
- Developing and maintaining standards for coastal flooding mapping
- Undertaking coastal risk assessments for the coastal zones.
- Supporting local council in preparing coastal flood plans based on coastal risk evaluations and local floodplain management procedures.

Catchment management authorities working together with Melbourne Water, local government and VICSES, undertake flood risk appraisals and gather information following coastal flooding and storm floods (Victorian Coastal Council (2008).

The Victorian coastline is around 2000 km in length (Galloway and Bahr, 1979), of which 96% is owned and managed by the state government. Over 85% of the Victorian population resides in the Victorian coastal area (Wescott, 2004). In 2006, the Victorian Department of Sustainability and Environment estimated the gross regional product (GRP) of the Victorian coastal ‘strip’ (defined as 5 km strip inland to the state boundary 5.5 km (3 nautical miles offshore) as approximately AU$ 9.0 billion per annum (DSE, 2006).

Wescott (2004) relates that two levels of agencies were established under the Victorian Coastal Management Act, to implement its objectives with state and local government: the Victorian Marine and Coastal Council (VMCC—the state-wide lead agency), and three supporting Regional Coastal Boards (RCBs—Western, Central and Gippsland Coastal Boards). The

VMCC was established to provide independent advice on marine and coastal issues to the Minister for Energy, Environment and Climate Change.

According to Habib et al. (2005), the VFMS requires Catchment Management Authorities (CMAs) and Melbourne Water to develop and periodically review Regional Floodplain Management Strategies (RFMSs) in partnership with LGAs, VICSES, regional agencies and local communities. The RFMSs are regional documents that are jointly prepared and implemented by all relevant agencies.

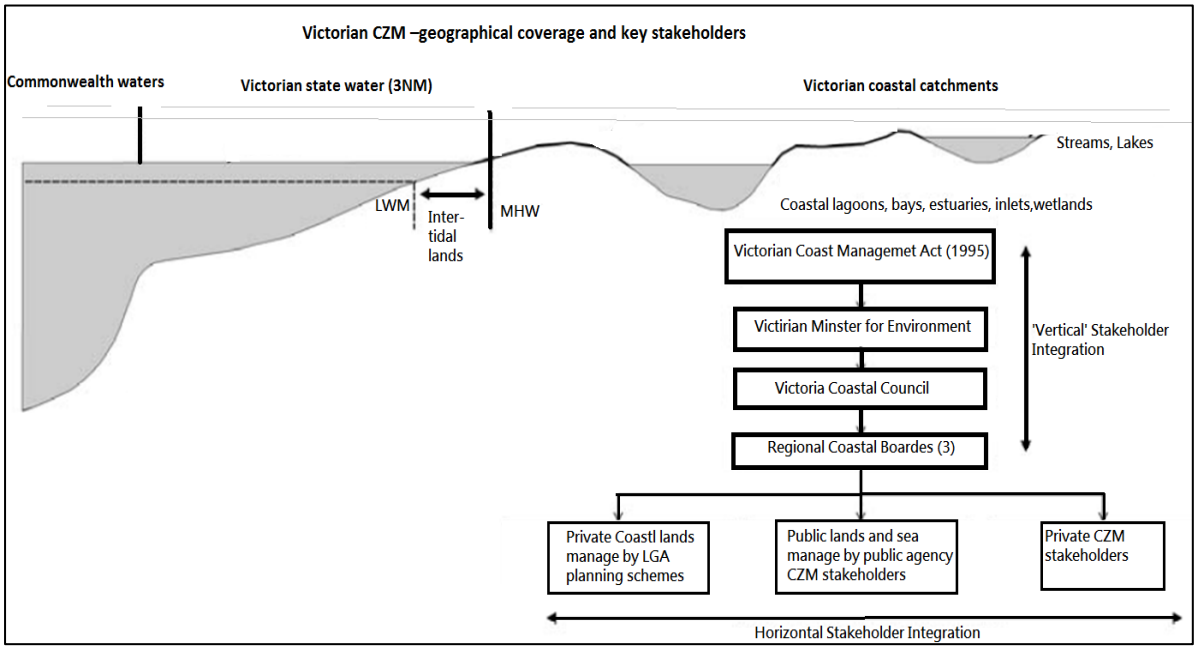


Figure:2-7: Structural diagram of the Victorian 'coastal area' (Modified from VCC, 2009).

LWM (Low Water Mark) and MHW (Mean High Water) associated with the corresponding horizontal lines in Figure 2-7. Floodplain management includes prevention, response and recovery activities:

- Prevention: Taking prudent actions to stop the incidents from happening, to reduce the severity of emergencies, and to mitigate their effects.
- Response: Fighting emergencies and providing rescue and immediate relief services.
- Recovery: The support of people and communities affected by emergencies to achieve a proper and effective level of functioning

These three primary activities are presented in Figure 2-8 below, as they relate to the flood. The diagram demonstrates the subset of emergency management which can be called flood management. It should be noted that the prevention, response, and recovery activities overlap.

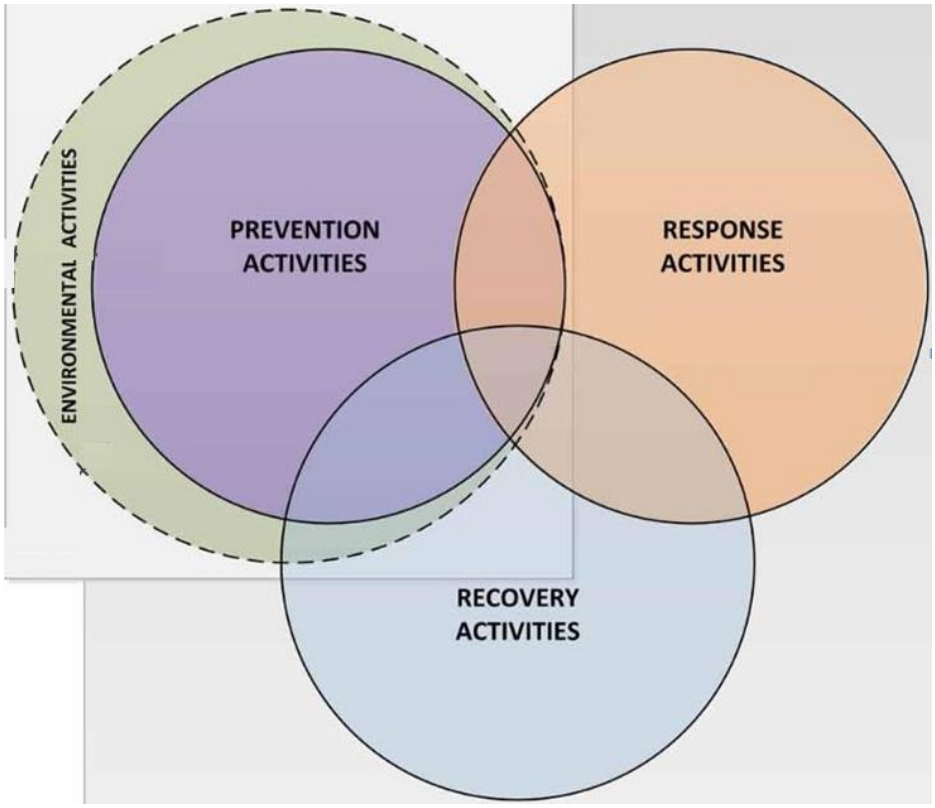


Figure 2-5: Floodplain management

(Adapted from the Victoria Flood management strategy, 1998)

Wescott (2004) argues that an important element of the VCC is to set up the Victorian Coastal Strategy (VCS), which provides direction for the state government. The role of the RCBs is to implement the VCS regionally and coordinate local contributions to decision-making. RCBs likewise create Coastal Action Plans (CAPs) which are key statutory plans under the VCMA. Key stakeholders include the Department of Environment and Primary Industries (DEPI), the Department of Transport, Planning and Local Infrastructure (DTPLI), the Department of Planning and Community Development (DPCD), Parks Victoria, and the local level CFRM including Catchment Management Authorities (CMAs), Local Government Authorities (LGAs), Ports Authorities, Foreshore Committees of Management (CoMs), and Water Authorities).

In Victoria, CFRM cuts across many jurisdictions and legislation, including both state and federal legislation. Coastal management occurs over water catchments, the shoreline and marine areas. In these terms, collaboration between stakeholders across the entire catchment-coastal-marine continuum is necessary for effective facilitation of the Victorian CZM program. Regional CMAs responsible for coastal management by virtue of their management of coastal-catchments (e.g. Glenelg-Hopkins, Corangamite, Port Phillip and Westernport, West Gippsland and East Gippsland CMAs), and LGAs with administrative areas spanning coastal catchments (17 in regional Victoria; 29 in metropolitan Victoria) are required to coordinate with fellow-stakeholders in Victorian CFM. However, Wescott (2004) and Awal and Ikeda (2003) argue that in Victoria, as the region of influence of the RCBs extends into catchment areas administered by other agencies, there is:

a) confusion over the role of the different agencies for the management of the coastal area;
b) ill-defined links between catchment and coastally focussed agencies;
c) poor coordination between management agencies, and
d) confusion between agencies due to responsibility and power issues.

Across the Victorian coastal area, successful stakeholder consultation is a vital prerequisite to facilitate effective CZM, and comprehensive coastal and marine spatial information is required to provide decision-support across a range of stakeholder aims. The Victorian CFM program will benefit from improved decision-support based on hydrological modelling. For example, data analysis and modelling can inform the decision-making process about environmental and disaster impacts. However, in Victoria, there are few state government-managed spatial datasets in coastal and marine areas accessible to CFM partners, as well as limitations in the Spatial Data Infrastructure. These limitations in information provision clearly inhibit the Victorian CFM program, both conceptually and operationally.

As discussed above, the Victorian Coastal Council (VCC) reports to the government on coastal and marine issues in Victoria. The VCS is established under the Coastal Management Act 1995. It provides a vision managing the coastal land use, and the responsibilities of stakeholders to help achieve that vision. The VCS calls for three important issues to be addressed, which are:

- Environmental change influencing impacts on the coast, including SLR;
- Rapid population growth in coastal regions; and
- The health of our marine ecosystems.

The VCS plans for the potential SLR of at least 0.8 meters by 2100 and takes into consideration the impacts of tides, storm surges, coastline processes and local conditions such as geography and topography while assessing risks and impacts related to climate change. The VCS also plans for SLR, causing an increase of 0.2 meters to overflow in flood levels by 2040 and the likely impacts on urban development and infrastructure.

The primary Victorian legislation managing climate change adaptation is the Climate Change Act 2010, which requires decision-makers to consider climate change in actions and plans under different Acts. It requires the creation of Climate Change Adaptation Plans for Victoria, to assess potential impacts, and understand state-wide needs and responses. The following sections discuss elements of Victorian coastal flood risk management.

2.6.1 Flood Controls in Land Use Planning

The rationale of the Land Subject to Inundation Overlay (LSIO) is to model which land is likely to be inundated and use this information to inform land use planning decisions. This includes restricting development in those areas to address the potential hazard risk. The Victorian Planning Provisions (VPPs) is a template for local government planning to develop locally appropriate zones and overlays in the planning scheme. Each planning contains a State Policy Planning Framework (SPPF) of state-level policies, plus local policies and planning tools such as zones and overlays. The State Planning Policy Framework is included in all metropolitan planning schemes in Victoria and contains policies related to flooding. These mirror the arrangements in the Victorian Coastal Strategy, in that there is a necessity to prepare for the potential SLR of 0.8 m by 2100.

Based on hydrological modelling the council, in discussion with catchment the management authorities (CMAs) and Melbourne Water, selected from the VPPs which flood overlays are the most appropriate to control development in flood risk areas. If the proposed development is within a flood overlay, a planning permit is required to subdivide land or undertake other types of land development. This triggers a referral to floodplain management authorities (e.g. Melbourne Water) who can refuse or approve with conditions.

2.6.2 Local government

The BCSC has projects related to land use and wellbeing and helps communities adjust to climate change in coastal settlements. These include:

- Working with the South East Climate Change Alliance;
- Amending plans to preparedness for climate change;
- Requiring coastal flood risk assessment for proposed developments (the two shires) or Section 173 Agreements (ie between council and developers) that prevent building on low-lying and flood-prone land (South Gippsland);
- Using the best available GIS data to distinguish zones of existing settlements that might be at risk of future coastal flooding, overland stream or coastal subsidence because of climate change;

2.6.3 Marine Spatial Planning Framework

The ‘Marine Spatial Planning Framework’ has been developed under the Marine and Coastal Act 2018 and aims to have integrated and coordinated planning and management of the marine environment. The Framework implementation includes updating the ecological, economic and social challenges in Victoria's marine environment. Under the proposition, existing organizations would keep on dealing with their duties in the different marine areas, but with reliable targets under the recent Act.

2.6.4 Relationship to Other Strategies and Plans

The lessons from 2010, 2011 and 2012 major flood events and the historical backdrop of flooding in Victoria illustrate that we need an effective system to manage floods, protect communities and save lives. Accurate data and information about flood risk must be utilized to

inform decisions about development and the location of infrastructures such as streets, control sub-stations, gas lines and telecommunications. To reduce risk to housing and infrastructure, all stakeholders need to address their risk factors. There are no convenient solutions for reducing risk related to flooding. The consistent message in emergency management reforms is that risk reduction is a mutual duty as illustrated in Figure 2-10. Practically speaking, the focus should be on explicit responsibility. Flood emergency management depends on outright clarity about who is responsible for what.

Local information is very important in helping understand inundation patterns and the alternatives for flood alleviation. It identifies problems in early warning while providing data on flood patterns. It is the government's job to capture this local knowledge. Community consultation under Regional Floodplain Management Strategies will help understand the gaps in knowledge and local needs.

Figure 2-6: Relationship between various State, Regional and Local activities

(Source: Victorian Floodplain Management Strategy Table 3).

	Minister for Environment, Climate Change and Water			**Minister for Planning**	**Minister for Emergency Services**	
STATE	**Victorian Coastal Council**	**DELWP**	**DELWP**	**DELWP**	**VICSES**	**Minister for Local Government**
	Coastal Strategy	Victorian Waterway Management Strategy	Victorian Floodplain Management Strategy	Policy and Victoria Planning Provisions (State Policy Planning Framework)	State Flood Emergency Plan	
REGIONAL	**Coastal Boards**	**CMAs**	**CMAs &DELWP**	**Regional Growth Plans**	**Regional Flood Emergency Plans**	
	Regional Coastal Plans	Regional Waterway Strategies	Regional Floodplain Management Strategies	Regional Growth Plans	Regional Flood Emergency Plans	
LOCAL	Local Councils	CMAs	CMAs and/or local councils	Local Councils	Local Councils	
	Coastal Management Plans	Works on Waterways permits	Local flood studies	Local Planning Policy Framework and local planning scheme controls	Municipal Emergency Management Plans	

2.7 Geographic Information Systems

Geographic Information Systems (Petroselli and sensing, 2012) are computer-based frameworks that can allow the creation, storage, management, visualisation, and modelling of all types of spatial information. They can be used to determine complex patterns or trends

within and between datasets (Wieczorek and Delmerico, 2009). GIS tools are increasingly used to assist decision-makers to best locate and manage soil and water assets (Setegn et al., 2008). The concept of GIS originated during the 1960's by Roger Tomlinson in Canada, Tomlinson's Canada GIS (TCGIS) was predominantly intended to map soil and timber resources and record land use relationships (Wieczorek and Delmerico, 2009). Prevalence of global GIS usage began during the 1970's when the tool started to be used by other professionals in similar fields.

Since its inception, GIS has evolved such that they now encompass complex spatial data frameworks, programming methodologies and have the capacity to execute intricate mathematical algorithms using high powered computers. As a result, the definition of GIS has evolved over time and some examples of GIS definitions include:

> *"Set of spatial tools for gathering, lodging, recovering voluntarily, changing and showing spatial information from this present reality for a specific arrangement of purposes"* (Burrough and McDonnel, 1998)
>
> *"…a sorted out gathering of computer equipment, programming, geographic information, and workforce intended to effectively capture store, refresh, control, examine, and show all types of topographically referenced data"* (Walker et al., 2016)
>
> *"Automated frameworks for the capture, storing and recovery of spatial information."* (Walker et al., 2016)
>
> *"spatial framework for information, storing, control, and yield of geographic data; a class of programming; a viable occasion of a GIS consolidates programming with equipment, information, a client, etc., to solve a spatial problem, support a decision, help to design."* (Goodchild, 1993)

GIS can be considered specialized software toolset that can be used to manage geospatial data (i.e. 'features' that represent real-world objects). The connection between each feature and its natural reference point on earth such as the atmosphere, biosphere, lithosphere, and hydrosphere are represented spatially therein (Wieczorek and Delmerico, 2009, Tait, 2005).

The two data models used are raster or vector data models store and analyse GIS data. Vector data utilizes points, lines, and polygons to represent the location or spatial feature in the map. Raster data models present data as pixels. Multi-band raster data are generally displayed with a mixture of blue, red and green, values that compose the image. In a high spatial resolution image, the number of pixels can be quite large, especially for LiDAR data DEM. The basic spatial data storage is usually more effective for vector data (points, lines, and polygons) forming the spatial features. Spatial statistic involves determining and understanding the spatial dependencies. Spatial regression analysis, network analysis, spatial clustering, and spatial statistics used to identify spatial autocorrelation. "Spatial analysis demands facilities for the input, management and display of spatially referenced data. All these services are currently available within existing GIS packages" (Goodchild, 2003).

2.8 Coastal Flood Management using GIS Embedded Hydrological Modelling

GIS technology (together with underpinned GIScience) is proven as an organization-wide, enterprise and enduring technology that continues to change how LGA operates. Government agencies have adopted GIS technology as a method to better manage the different department of government organization (Holdstock, 2016). During the 1960s to 1970s, GIS and hydrological modelling developed separately using different processes (Sui et al., 1999). Since that time there has been significant research about the combination of GIS with hydrological modelling starting in the late 1980s (Weng, 2001). This came out of GIS researchers efforts to improve the analytical capabilities of GIS and an increase in interest from hydrologists inaccurate spatial digital representations of the landscape (Bhatt et al., 2014). These days, both GIS users and hydrologists have recognized the common advantage of incorporation (Prodanović et al., 2009). Different hydrological modelling strategies have empowered GIS users to go past the information inventory and the management stage to enhanced modelling and visualisation (Sui et al., 1999) the ability of GIS to process DEM information has provided hydrological modellers with improved ways to develop information that is very useful for decision-makers (Petroselli and sensing, 2012).

The ongoing development of GIS provides the potential to make hydrological models increasingly transparent and enhance the communication of their results with users. The developing literature on the combination of GIS with hydrological modelling bears witness to the shared advantages (Sui and Maggio, 1999). Bartlett and Smith (2004) consider that within coastal area frameworks, ready access to relevant, reliable and timely data and information is of importance so that both policies and management can be based on informed decision-making. It has also been noted by Kenchington and Crawford (1993). Unfortunately, due to the dynamic nature of the coastal area, the data and information to support decision-making are often inadequate. This means that important decisions are made by coastal managers based on inadequate information available because the information is demanded faster than technology can provide it. However, by using computer-based digital spatial information and supporting technology, such as GIS embedded hydrological modelling, a decision-support capacity is possible that allows analysis that was not possible before. This can be made available quickly and on-demand for supporting stakeholder coastal area decision making (Bartlett and Smith, 2004, Caton and Harvey, 2015).

The integration of GIS, LiDAR, hydrology and numerical models allow for a wide scope of data models to help decision-making (Campagna, 2005). Many authors have discussed the institutional aspect of geospatial technology such as GIS and remote sensing. For example, (Carter, 1989) defines a GIS as “an institutional entity, reflecting an organisational structure that integrates technology with a database, expertise and continuing financial support over time”. This definition provides an important focus on the organisational context of GIS deployment. ESRI (2016) suggest that this organisational perspective has five dynamic elements for consideration: 1) data; 2) information technology; 3) standards; 4) people with GIS skills, and 5) an organisational background.

Continued advances in software and hardware capabilities, especially in the late 1980s, led to the commercial viability of GIS (Campbell, 1990). The model is combined with ArcMap to empower pre-handling of GIS information, for example, measuring the spatial contributions of land use, soil and elevation, and applying the model's spatial parameters, for example,

Manning's and overflow coefficients, time of movement, stream speed and surface-related parameters (Nyenje and Batelaan, 2009). Fundamental model goals are:

1) To give a comprehensive GIS-based process for flood forecasting and watershed predictions on a catchment scale. This is a productive way to use GIS innovation and remote sensing data.
2) To empower the utilization of the model for the generation of the spatial representation of hydrological forms, for example, runoff, soil dampness, groundwater energy, and so on
3) To model land use and climate change effects and hydrological impacts.
4) To accommodate a model that can operate on a variable time scale, cell scale and a semi-distributed model on the small sub-watershed scale (Liu and De Smedt, 2004).

This helps set up watershed management plans. The model was initially created by Batelaan et al. (1996) and used for flood forecasts by De Smedt et al. (2000) and Liu and De Smedt (2004). It has been connected to tropical conditions by Lai et al. (2005), for examining the impacts of atmospheric changes on streamflow by Gebremeskel et al. (2005) and for stream generation in the hilly terrains of central Europe. It was used for simulation of reforestation impacts on floods by Bahremand et al. (2005), Bahremand et al. (2007), Bahremand and De Smedt (2008), and for prediction of phosphorous transport by Liu et al. (2006).

Application of the GIS-based hydrology model on a small catchment at Inverloch, Victoria, on a daily time scale, is presented in this study. GIS-based hydrology and enabling technology is recognised by researchers and key organisations as being suitable, and indeed essential, for deployment in a decision-support capacity in CFM programs worldwide (Bartlett and Smith, 2004, Cicin-Sain et al., 1998, Vellinga et al., 2008). It is also useful for GIS Embedded Hydrological Modelling for Coastal Floods in Victoria.

The central characterizing idea in CFM is the powerful combination crossover of controls, organizations and partners for the economical utilization of coastal areas and assets (Brown, 2005). He argues that on a global and local scale, CFM success in meeting the challenges presented is usually proportional to the strength of decision support frameworks emplaced to

monitor environmental changes. Both inter- and intra-agency data integration must occur if rapid coastal flood assessment and prediction are to be provided.

In Victoria, there have been many years of public spatial infrastructure policy initiatives culminating in the VSIS (2005), and significant Victorian policy evolution and innovation regarding CFM, (e.g. CMA, 1995; VCS, 2002), which has taken place since the UNCED (1992). However, studies by Wheeler (2005a, 2005b, 2005c, 2006), Wheeler and Peterson (2005b, 2005c), and (Wheeler et al., 2011) have identified that at Victorian local CFM stakeholder agency level, the adoption and use of GIS-based hydrological modelling, and inter-organisational spatial data sharing/exchange is currently taking place in an ad-hoc, uncoordinated fashion, despite state government-mandated 'top-down' approaches to GIS technology diffusion and spatial data handling, e.g. refer to Chan (1998). This research by Wheeler and Peterson focuses on integrated (multi-risk) analysis related to coastal zone management. The research in this thesis has been informed by their research and is focussed on flood risk based on refined hydrological connectivity.

There is an overwhelming realisation amongst key Victorian spatial industry stakeholders that the provision of spatial information can have a profound effect on stakeholder decision-making (Woodgate and Coppa, 2008). However, in Victoria, no research has yet been carried out to determine the current situation regarding the use of GIS technology for CFM decision support, or to gauge diverse CFM stakeholder 'user requirements' information, for possible integration into future 'top-down' spatial data handling policy development strategies (Thomas and Sappington, 2009). The status of GIS technology implementation as a key integrative decision support tool amongst Victorian CFM stakeholder agencies thus remains fragmented and uncoordinated. It varies considerably from agency to agency according to a range of factors, hitherto vaguely recognised and unquantified in the eyes of policy-makers and researchers.

GIS embedded hydrological modelling (GEHM) is a decision support tool that will help model coastal flooding. It is a river basin model developed to simulate the effect of land development on everyday water flow and residue and watersheds (Arnold et al. (1998).

Hydrological models (SWAT and Arc Hydro) use GIS-based interfaces and GIS embedded of computerized risk models to delineate a watershed into sub-basins that are further partitioned based upon soil types and land use, into regions of similar hydrological attributes, called hydrologic reaction units (HRUs). HRUs are segments of a sub-basin that have interesting blends of land use, management, and soil characteristics. GIS-based operations are then used the stream slope, length and geometrical dimensions, accumulation area, and aspect. This research on GEHM involves employment of LiDAR and other data to upgrade and refresh the portrayal of HRUs in selected watersheds of Victoria. Likewise, hydrology shows the yield information is being modelled and visualized in new web-based applications that can be effectively shown using a web browser (McGuire et al., 2014). Ideally, watershed models should assess the impacts of topography, soil on water runoff.

GEHM is a physical model to assess the impacts of topography, soil precipitation, runoff and evapotranspiration for both basic and complex landscapes. The GEHM model was initially created by Wang et al. (2011) and further developed by specialists of flood forecasting and streamflow simulations (Bahremand et al., 2005, De Smedt et al., 2000, Liu and De Smedt, 2004, Liu and Todini, 2002). The model uses numerous layers to characterize the water and energy balance for every grid cell, considering the procedures of precipitation, interference, snowmelt, depressions, invasions, evapotranspiration, permeation, surface overflow, interflow and groundwater streams (Correa and Adhityawarma (2004).

In summary, knowledge gaps exist in Victoria for the application of GIS-based hydrological modelling for CFM stakeholder decision support. Currently, GIS and hydrology integration is not occurring with the consistency demanded by the international, commonwealth or state policies.

2.9 Why LiDAR is Important for Hydrologic Connectivity in Coastal Systems

A precise digital model of the coastal zone's elevation is necessary to assess the risks of flooding, given that the water will move to lower regions following flow pathways. The production of a Victorian DEM was an essential undertaking that was recognized by the Australian government for national hazard appraisal (French et al., 2013) DEMs have been generally utilized over the last 20 years. They give a three-dimensional model of the geography of the terrain and can be developed utilizing a plethora of energy, for example, photogrammetry, radar and satellite imagery. DEM is critical for understanding the possible impacts and exposures of coastal flooding caused by storms, flood events and SLR (Poppenga et al., 2010). Therefore, government and state organizations are progressively depending on LiDAR remote detecting innovation to portray flood zones and create rules for flood chance evaluations (Xian et al., 2015).

Coastal managers are responsible for moderating risks to the community and the coastal environment, and they depend on forecasts of coastal flood mapping. For that purpose, LiDAR elevations are fundamental for modelling the volume of water flow across the landscape to assess coastal flooding chances (Poppenga et al., 2014). The veracity of coastal flooding expectations, in any case, depends upon flood modelling techniques that clarify the hydrological network of seawaters and inland in a highly detailed LiDAR elevation surface (Poppenga et al., 2014).

Achieving hydrological connectivity with a hydrologic process, which simulates overland surface flow using high-resolution LiDAR-based DEM (Poppenga et al., 2014) in locations that have become impounded by elevated features (streets/bridges) which would flood on only certain events (Poppenga et al., 2010). Despite the good vertical accuracy of LiDAR height surfaces, there are difficulties in recognizing areas that will be flooded in a DEM (Poppenga and Worstell, 2015, Poppenga et al., 2014).

A common problem experienced in LiDAR DEM hydrological modelling is raised structures, for example, streets lying over underground drainage systems (Poppenga et al., 2010, Diaz-Nieto et al., 2011, Abdullah et al., 2012). Diaz-Nieto et al. (2011) solve this problem by using a water balance method to construct a screening tool for flood risk identification. They say that this approach will avoid the complexities of modelling overland flows in coastal urban environments. They used a combination of water features that were 1 meter wide and Google Earth images to determine the overland flow paths around elevated bridges or roads and assumed that the LiDAR DEM was correct (Diaz-Nieto et al., 2011).

However, this did not directly address the hydrological connectivity between upstream and downstream areas surrounding culverts. Abdullah et al. (2012) developed digital terrain models (DTMs) for urban flood modelling using LiDAR point data filtering techniques. Their approach consists of a data fusion that combines the LiDAR intensity, slope and height. As opposed to utilizing computerized techniques to distinguish raised structures, they created vector waterway polygons on the LiDAR point cloud information.

Abdullah (2012) and Poulter (2008) found that the use of DTMs for flood modelling applications may not always be appropriate depending on the terrain features. The ‘bathtub fill’ SLR model (single standard surface method) is where the lower parts fill up first. This involves land that is hydrologically connected to coastal land and forcing coastal flooding to only occur there (Gesch et al.,2012). Poulter (2008) identified that LiDAR flood data is sensitive to horizontal resolution and the modelling of hydrological connectivity. Hydrological connectivity resulted in the flood being relatively close to the enforced drainage network for the hydro-corrected DEM. This indicated that the “bathtub fill” method does not reflect other factors such as the surface hydrological connectivity between certain sea grid cells (Gilmer and Ferdaña, 2012). This can create incorrect modelling of the flooding areas that are not linked to the ocean, such as inland areas which require the drainage to the ocean. Water level change due to seawater flooding ("bathtub fill") will lead to flood uncertainty by simply increasing the level of water. The issue was taken to identify hydrologically detached areas within a boundary and mention that they should be considered for the coastal flood.

2.10 Chapter Summary

This Chapter described the issues facing Victorian coastal floodplain management. Understanding the policies of relevant organizations is important for coastal flood management. The Chapter also discussed GIS-embedded hydrological modelling for coastal flood management in Victoria. Hence, this Chapter contributes to answering the intermediate research question “What is the current status of integrating GIS with hydrological modelling and multi-source spatial data systems?" (Section 1.2.2).

This Chapter also reviewed the evolution of integrated approaches to flood management, coastal climate change and specifically coastal flood management (CFM), with special emphasis on CFM policy development, within Australia, and within the state of Victoria. The importance of relevant and timely information, including GIS embedded hydrological modelling, for CFM stakeholder decision-making, has been recognised, in national and state policy.

While the benefits of GIS-embedded hydrological modelling for CFM is recognised, good examples are lacking. Limitations in how existing GIS are interfaced with hydrological models constrains how hydrological models are created. This represents a major policy-to-practice gap and constrains the effectiveness of the Victorian CFM program. GIS-based hydrological modelling will support new computational models and analysis techniques that are computing-platform-independent. The spatial-temporal frameworks embedded in the current generation of GIS will enable us to improve hydrological sciences, adopt GIS advancements and seek imaginative applications pertinent to societal CFM concerns.

Victorian local governments are responsible for coastal flood management and would benefit from the development of this research on GIS-embedded hydrological modelling to support flood-risk based coastal planning. The next Chapter introduces the local government selected as a case study area for this research and discusses the criteria for the selection.

Chapter 3

3 Pilot study area: Bass Coast Shire Council

3.1 Introduction

In Chapter 2 it was established that governments are primarily responsible for managing hazards to public infrastructure, delivering government facilities, and conserving the environment. Therefore, local governments need to understand and respond to the impacts of climate change. Developing an effective spatial approach to model the impacts of climate change is needed. Spatial Decision Support Systems (SDSS) improve hydrological and vulnerability mapping and multi-criteria problem solving. GIS tools assist in the spatial visualization of the impacts and provide information for coastal zone management. The Bass Coast Shire Council (BCSC) was selected for a pilot study on managing hydrological data for generating flood inundation and hazard maps to assist flood risk planning.

According to a recent report from the Western Port Greenhouse Alliance and the Gippsland Coastal Board (Brooke and Kinrade, 2006), the BCSC will experience significant climate change impacts this century. The release of the Victorian State Government Coastal Strategy in November 2008 identified the potential effects of climate change. Reports also confirm that SLR, changes in rainfall patterns, intensity, storm severity and rising heatwaves will have an impact, especially in communities in coastal low-lying areas that are at risk of flooding. Thus, local government planners in the BCSC have called for the development of a spatial decision support tool to provide an overview of areas that might be possibly exposed.

The BCSC was selected as the research pilot study area, based on a Western Port Greenhouse Alliance and the Gippsland Coastal, BCSC report and other climate change predictions (Brooke and Kinrade, 2006). The report also describes the potential changes to sediment movement patterns along the coast, as well as the potential effects of SLR on physical resources and biodiversity along the coast. SDSS using hydrological models of flood-risk and SLR impacts on land use support decisions about remediation of these threatened resources. In this Chapter, the criteria on which the BCSC was chosen as a pilot study area is presented, and the benefits of using a case study approach discussed.

3.2 Pilot study area location

The BCSC is a rural Council south-east of Melbourne near Western Port Bay and covers around 864 square kilometres (Figure 3-1). The BCSC border extends northward to the Great Dividing Range or the Eastern Highlands, and south to the Bass Strait. Port Phillip and Westernport Bays fringe the BCSC on the western side and along the eastern boundary is the South Gippsland Shire. The BCSC has varied topography and a mix of rural and urban land use types (Council, 2008).

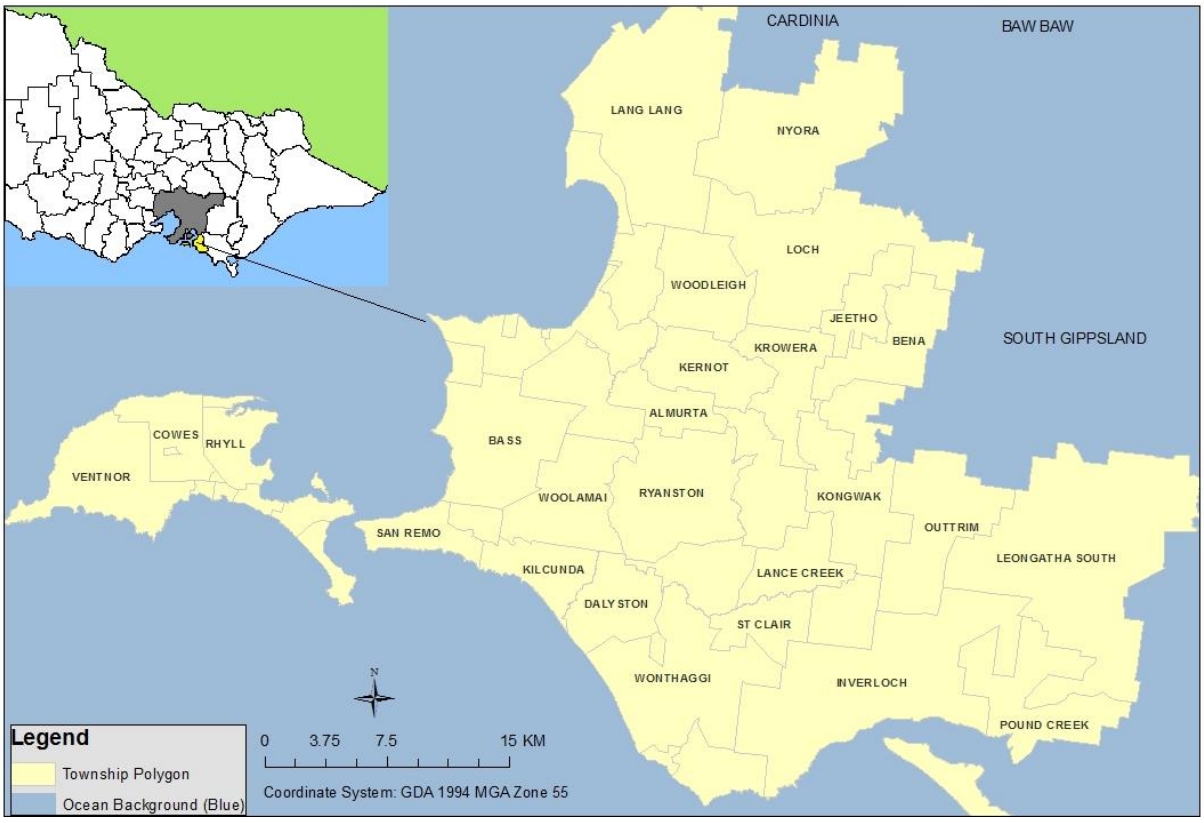


Figure 3-1: Location and extent administered by the Bass Coast Shire Council (BCSC)

According to the Australian Bureau of Statistics (ABS), the population of the BCSC in 2016 was 32,804 people, living in 25,817 homes, with an average family size of 2. The area is a rural coastal Council which contains numerous tourist attractions, notably Phillip Island. Around 35% of Melbourne's international guests visit the shire (DPCD, 2012a). The larger towns in the shire are Cowes, San Remo, Wonthaggi, and Inverloch.

3.2.1 Population and Growth

BCSC has experienced unprecedented development along the coast over the past decade. This population development along with increased tourism in the coastal area is putting pressure on BCSC coastal communities. Figure 3-2 outlines the BCSC population for 2018 is 34,447 and is estimated to increase to 46,429 by 2036. The rise in household income, access to innovation and improved transportation connections with Melbourne, has helped to accelerate coastal development (BCSC, 2019).

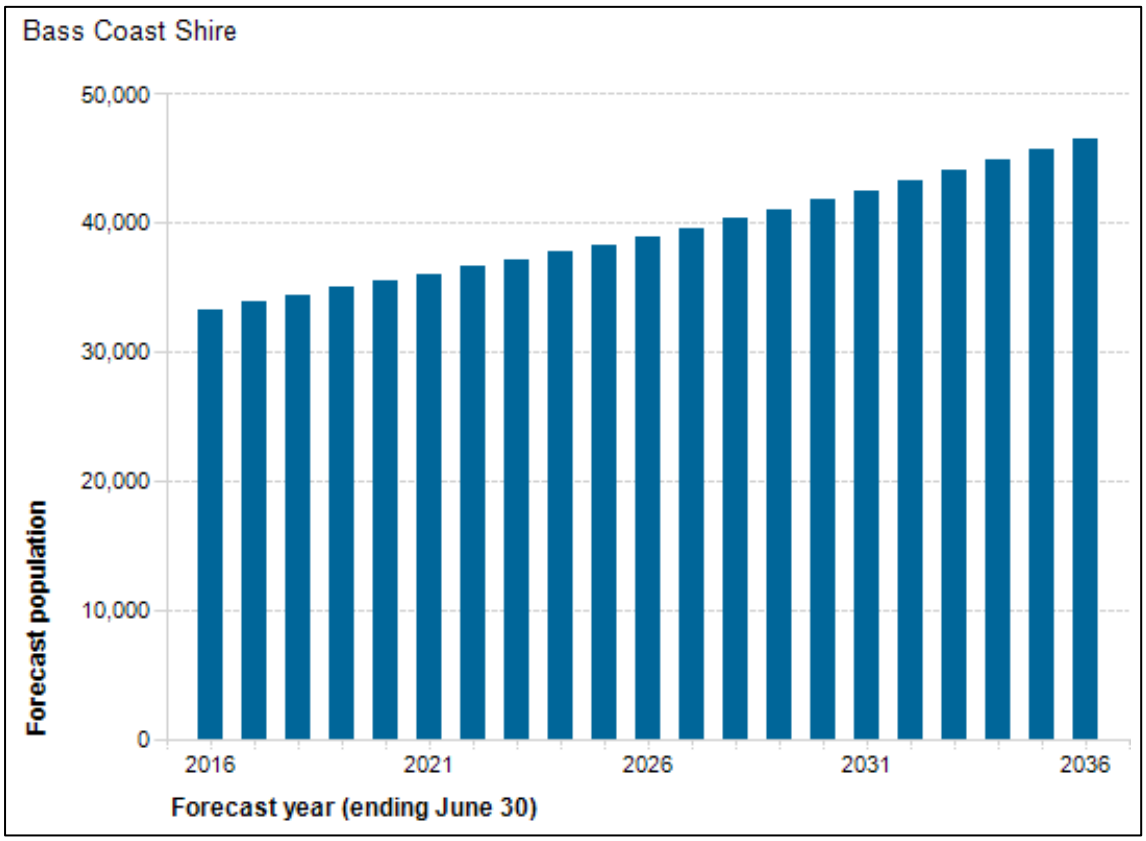


Figure 3-2: Population forecast in 2016 showing a projected increase to 2036.

Source: BCSC, 2019.

3.2.2 Urban development

Like other Victoria peri-urban local governments, land use change is a challenge for the BCSC. With the conversion of farming land into hard urban surfaces through land development,

stormwater overflow increases in terms of duration, flow rate, overall volume, frequency, erosion and pollutant transport. Furthermore, the demand for coastal land has increased due to urban growth (Butt et al., 2009).

Among Melbourne's peri-urban local governments, the BCSC had the highest growth rates between 2001 and 2006 (Buxton et al., 2011). The BCSC had the highest growth rate of all Victorian shires due to attraction of moving to the coast (Berwick, 2007). Coastal gateways are located close to the large city centre (for example, Melbourne), with many residents working from home, and high suitability for retirement (Grunbuhel et al., 2010).

The BCSC area is exposed to rising sea level risks, flash flooding, and coastal riverine floods (Pourali, 2014). As described in Chapter 2, the BCSC is the authority responsible for land use planning and must manage the risk of flooding in their urban and urban-rural areas. Therefore, the Council works closely with other agencies responsible for flood management in implementing coastal flood management.

3.2.3 Agriculture

Agriculture is an important element of the local economy producing around 7–8% of the local GDP. The biggest contributors to this economic sector are dairy ($52 million) and meat ($28 million) (RMGC, 2013). Most of the agricultural land in the BCSC is considered as highly productive rural land, especially west of the Bass Highway. As a result, the area has a concentration of dairy-related industry and is connected to the wider Gippsland dairy industry (RMGC, 2013). The future of agriculture in this area is projected to remain strong, however, the encroachment of urban growth is an issue for BCSC.

3.2.4 Tourism

The tourism industry is a mainstay of the BCSC economy with internationally renowned attractions, especially on Phillip Island. Tourism contributes around $620 million directly to the local economy, and over $1 billion to related industries. Tourism supports around 1,400 jobs every year (RMGC, 2013).

3.2.5 Environment and Landscape

BCSC has natural environment and landscape attractions of local and national significance, including Ramsar wetlands, marine parks and state parks. The Rural Land Use Strategy aims to secure ecological resources and limit the effects of climate risks (BCSC, 2013). The geography inside the BCSC incorporates pink stone and basalt with significant landforms including the Pinnacles, Colonnades and Pyramid Rock on Phillip Island, with peat and coal inside the hinterland (Council, 2008).

BCSC has important fossil deposits along the coastline at Inverloch, Flat Rocks going back to an ancient period (Council, 2008). The most recently discovered dinosaur at Flat Rocks is a small plant-eater in the Hypsilophodont family (Council, 2008). Until the 1800's the Great Forest of South Gippsland' was a barrier to the settlement from the north (Council, 2008). Eucalyptus, for example, Bluegum and Manna gum trees more than 100 meters tall grew in large numbers to the south-west. Mountain Ash trees were located in the north and east of the Shire, with stands of cool and mild rainforest (Council, 2008). During the 1890s land, clearing prepared the way for early settlement allowing for cultivation and mineral mining to take place. During the 1900s land-related issues emerged, including salination of pastoral land, soil erosion and loss of soil carbon (Council, 2008). European settlement introduced pest plant and animal species, including rabbits, deer, boxthorn, blackberry and gorse (Council, 2008). Today less than 10% of indigenous vegetation remains from pre-1700 (Council, 2008).

3.2.6 Climate Change in the BCSC

Environmental change and climate change are key issues for biodiversity conservation throughout the world (Heller and Zavaleta, 2009). As discussed earlier, the BCSC is confronting several impacts of climate change and is considering long-term adaptation and mitigation interventions to manage these changes. Under most of the likely anticipated climate change scenarios, Bass Coast will encounter increases in extreme climate change events, increased risk of coastal flooding, increased erosion of shorelines, more heatwaves, bushfires, dry seasons, floods and changes to precipitation patterns, more serious threats to water supply, impacting the elderly, indigenous people and the sick and frail. Soil and coastal erosion will impact much of the area used for recreation (Parks Victoria 2010). Loss of coastlines and hills

by erosion will change how individuals can utilize them. Changes in vegetation may make regions more fire-prone. Climate change may also encourage new investment opportunities in the region. Examples include renewable energy sources, expanded number of businesses working in sustainability, expanded focus on ecotourism, public transport and infrastructure, better organic waste management, and federal and state government opportunities driving mitigation, adaptation and education projects.

3.2.7 Control of coastal flooding in the BCSC

Development in low-lying coastal zones is controlled using planning scheme zones and overlays (Macintosh, 2012). The Land Subject to Inundation Overlay (LSIO) controls development in flood-prone coastal areas encompassing Bass River, Newhaven, Cowes and Silver Leaves, Powlett River, Inverloch, and Mahers Landing. Specifically, the Council is required to issue a permit for any development including the construction of new structures, earthworks and subdivisions.

The LSIO provides permit triggers for development that may or may not be affected by floods or predicted coastal floods (Sterr et al., 2000). Applying an overlay provides Council with an opportunity to consider the potential impact of flood hazard. It will also provide an opportunity for Melbourne Water and the West Gippsland Catchment Management Authority (WGCMA) to provide advice and recommendations to the council as a referral authority, Habib et al. (2005). According to Council's Director of Planning and Environment: "*Given that BCSC is currently in receipt of mapping that outlines the extent of the flooding across the municipality, it would be an unacceptable risk to not attempt to apply a planning control that would address this"* (Duncan-Jones, 2013).

Maps created by the Council's GIS group use information provided by WGCMA, Melbourne Water and the previous state government DELWP. "*The amendment is being progressed to address issues associated with riverine flooding and coastal inundation effects from predicted SLR. BCSC has a duty of care to ensure that current riverine flooding and SLR information is available to the community" (Duncan-Jones, personal communication 2013).*

The main point is to apply the flooding information to ensure the LSIO is correct throughout the BCSC are in terms of potential riverine flooding and coastal inundation. Ms Duncan-Jones (2013) noted, "*Inclusion of this information in the planning scheme allows landowners and developers immediate access to the necessary information about riverine flooding and SLR in the early stages of the development process"*.

The new development is designed with flood risk in mind when the application of the Land Subject to Inundation Overlay will ensure that. "*Given that the mapping is readily available, applying the appropriate planning controls will ensure that the council is making informed decisions at the planning permit stage based on the best available information. This, in turn, will ensure that council and ratepayers are protected against the financial and social impacts, as well as the liability of planning decisions that do not take flood risk into account"* (Duncan-Jones, 2013).

The key flooding challenges and the roles of stakeholders are set out in BCSC's flood management plan. One of the priority actions in the local flood management plan is the identification of overland water flows. BCSC must assess overland flows for every township in the Shire. Flood mapping information is essential for effective flood management, providing advice to the affected properties and networks, and to undertaking flood mitigation. Council manages 100 hectares of bushland and 42 kilometres of coastline. Several agencies are responsible for foreshore management along the Bass Coast as illustrated in Figure 3-3.

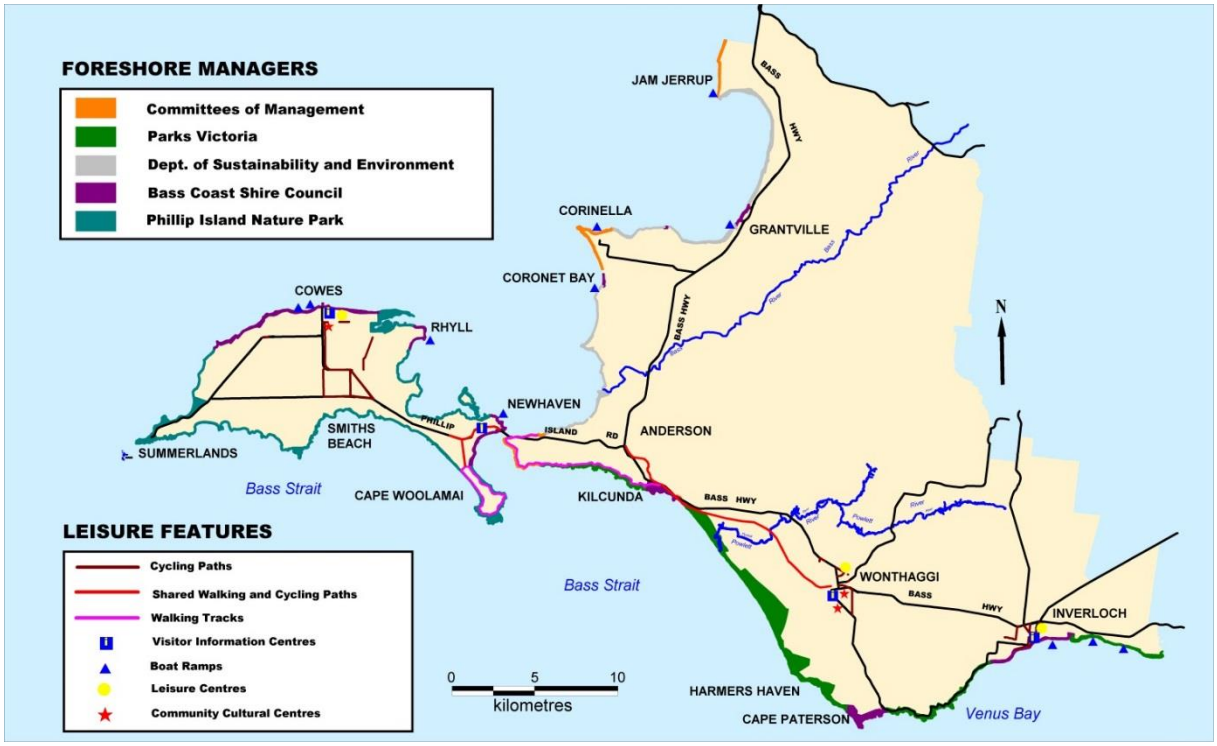


Figure 3-3: BCSC Coastal Reserve Management, Source: BCSC, 2013.

3.2.8 Assessment of the risk of climate change and adaptive planning

Council undertakes an assessment of climate change effects to understand the risks and identify where to implement adaptation. Hazard assessment and adaptation are undertaken at regular intervals to inform action planning. Council undertakes community consultation related to climate impacts and provides advice on managing risks so that existing practices can be modified. Council manages 42 kilometres of foreshore reserves, as well as several bushland reserves including Ventnor Common, Saltwater Creek Reserve, Thompsons Reserve and Ayr Creek Reserve. The Environment Team's role in the management of these reserves includes:

- Biodiversity management
- Bushland rehabilitation including indigenous revegetation programs.
- Environmental weed control and pest animal management, including an ongoing rabbit control program.
- Protection of rare flora and fauna and including a program to protect Hooded Plovers, particularly during the breeding season.

- Protection of indigenous vegetation including action to address illegal vegetation removal and encroachment into reserves.
- Supervision of the leases for the Cowes, Phillip Island (Newhaven), Kilcunda and Inverloch Caravan Parks.

3.2.9 Climate Change Mitigation and Adaptation by the BCSC

The BCSC is involved in gathering data and preparing regional reports with a risk management approach. BCSC also provides information to residents and developers and will continue to develop and implement awareness programs. BCSC has identified the local impacts of climate change and is examining what adaptation responses can be made to reduce the risks to the community. Consultation through workshops with local emergency response agencies aims to identify the local impacts and adaptation needed. Using the information gathered the Council prepares a Climate Change Impacts and Adaptation Framework for Action for Council operations. The framework will include documenting policy direction and urgent works/processes and identifying skill and resource requirements and priorities for the short and long term. Key environmental changes forecast for the Bass Coast include:

- Generally hotter days and more frequent and severe heatwaves.
- Generally drier days and more frequent and severe droughts.
- Increased bushfire risk.
- More serious catchment flooding in rivers and floodplains.
- SLR for Bass Coast. – 0.8 m by 2100
- Coastal storm-related floods and foreshore degradation/subsidence.

3.3 Spatial Knowledge Management by BCSC

In 2011, the BCSC won the Asia-Pacific Spatial Excellence Award and was a finalist for the Victorian Coastal Awards for Excellence in 2012 (Pourali et al. (2014a). This award was for the development of spatial applications for flood management. The Bass Coast GIS group built an enhanced spatial database, giving access to new data and spatial information that informs future planning and land development for coastal areas (Municipal Association of Victoria, 2012). While the collection of detailed survey data for the entire coastline is not an

economically viable option, new technologies provide opportunities. The use of LiDAR data to map the predicted inundation extent is a common approach in regional and metropolitan flooding Planning Scheme Amendment applications when survey information is not available. Recent amendments to LSIO in planning schemes have relied on LiDAR mapping in the local government areas or Casey (Amendment C143) and Wellington (C33). LiDAR technology is accurate vertically to 0.1 m (10 cm). However, the accuracy of the mapping was challenged by RMIT research students (Ussyshkin and Smith, 2006), who recommended that it be used for applications that don't require vertical precision to be better than half a meter.

The Future Coasts Strategy, based on a LiDAR data model, is a high-level assessment of the potential risk from SLR and storm surge at a state-wide and regional scale for four different periods (2009, 2040, 2070 and 2100). This risk assessment is very useful for BCSC's local risk management, water management and land use planning.

BCSC also initiated the use of the Future Coasts LiDAR information as fundamental data for Council staff to make more educated planning decisions. That prompted the Victorian Coastal Inundation information (2012) and the Bathymetric Survey information (2008) being utilized to develop a hydrological model of the water surface of Western Port for 1% AEP immersion. Water Surface Elevation was modelled at a 1:25,000 mapping scale, simulating and integrating 20cm, 40cm and 80cm SLR situations (Demonstrated by Water Technology Pty Ltd). This modelling was then used to help BCSC improve its Land Subject to Inundation Planning Overlay (LSIO). Further, GIS tools and the analysis of land use changes associated with climate change have helped to strengthen Asset Management programs, especially about:

- The use of Water Sensitive Urban Design (WSUD) to control overflows and water quality.
- Drainage Detention to reduce downstream flooding.
- The Building Asset Management Plan 2016 recognizes climate change as a risk and suggests the utilization of Environmentally Sensitive Design (ESD) standards in the council's operational and capital works.

Whether the LiDAR data should be used to inform decisions about individual properties or other structures has been a major point of concern for affected landowners and objectors who have argued that it should not be used to inform the application of a planning overlay. However, it should be noted that the overlay isn't the final word as the overlay merely flags potential flooding issues that should be further assessed when making planning decisions concerning the property. The key point is that the overlay is used as a planning permit trigger only.

The provisions of the Land Subject to Inundation Overlay state that the following must be provided with all development applications for which a planning permit is required by the overlay: "*Elevation plans showing natural ground level, (any proposed) ground level and the floor levels of any proposed buildings in relation to Australian Height Datum, taken by or under the direction and supervision of a licensed surveyor" (BCSC, 2019).* This means that detailed survey data will be required as part of development applications that are triggered by the overlay. It is this information which will be used to inform decisions regarding the development application.

3.3.1 Benefits of the Pilot Study in Terms of Spatial Knowledge

As discussed above, building spatial information about the coastal landscape is vital to support Victorian agencies to achieve the goals of the Marine and Coastal Strategy (Wheeler and Peterson, 2010). Access to long term projections and spatial analysis on the state of the coastal areas, including the physical and biophysical conditions, can improve the management of the coastal areas in several ways. Monitoring the condition of the ecological asset establishes a baseline that helps to identify changes over time and to identify the flood risk impacts. In coastal areas, benefits of this information include:

- More adaptive management—having accurate information on the changing conditions and the impact on natural resources would enable BCSC to distinguish risks, undertake adaptation and monitor the effectiveness of these activities.
- Improved public land management - for example, the condition of protective and recreational assets along the coast can be monitored to inform where upgrades or rebuilds are needed.

- Emergency readiness – Monitoring and analysis of waterfront flooding and degradation after storms, algal blooms or marine nuisance invasions, and predict future problems. Spatial analysis can be utilized to plan or more adequately react to these events.
- Planning for climate change—information on changes over time provides a better understanding of the impacts of climate change and enables practical management plans to be developed. Marine Spatial Planning (MSP) is a method for dealing with the improvement of marine areas. Marine spatial planning incorporates three-dimensional spatial arrangements for marine stakeholders and sustainable ecosystems.
- Using spatial data and analysis, an MSP Framework can direct future arrangements and resolve issues in marine and coastal management. MSP incorporates management of social, economic and environmental considerations to protect a sustainable ecosystem and allow stakeholders to carry out their activities (see Figure 3-4).

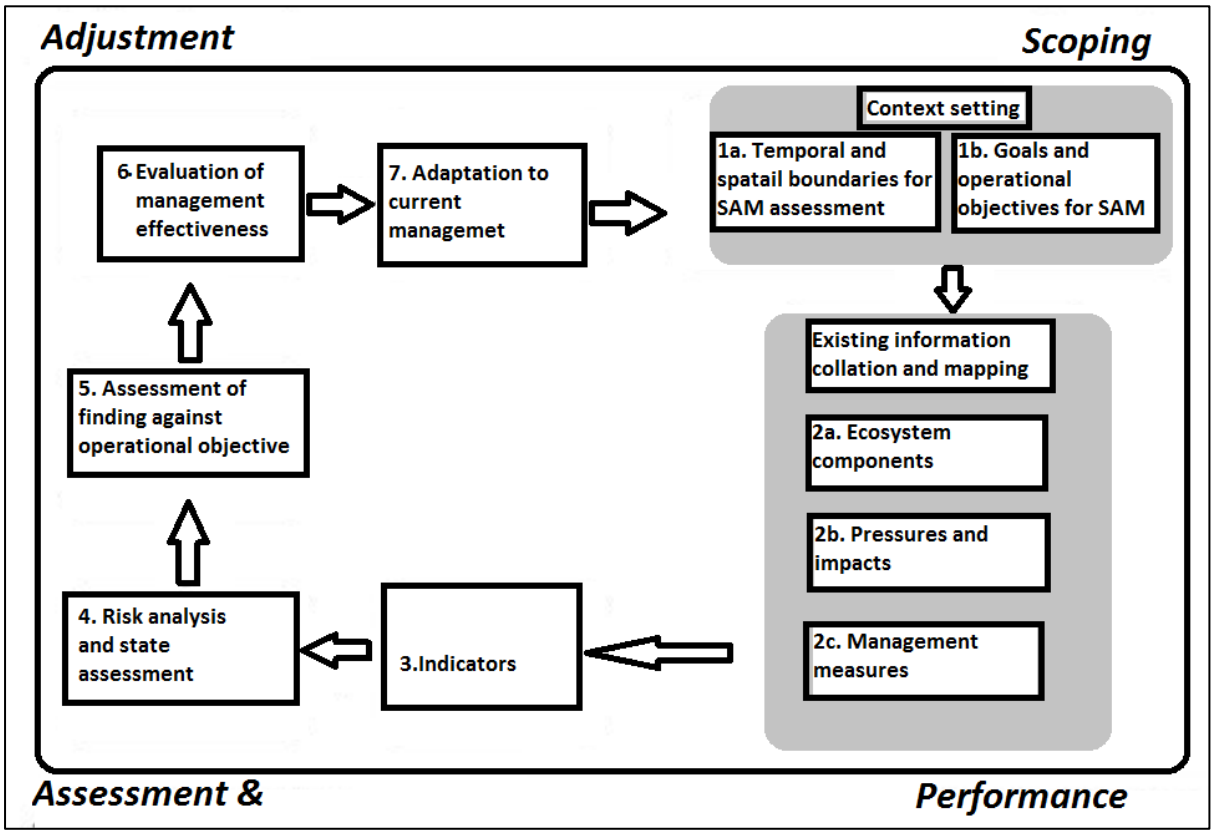


Figure 3-4: Tools for Marine Spatial Planning and Spatial Assessment Methodology (SAM), adapted from (Pınarbaşı et al., 2017).

3.3.2 Why is a Pilot Study in Spatially Related Applications Important?

Both natural and constructed coastal assets are under increasing pressure from a growing population. The BCSC already experiences severe storms caused by low-pressure systems which can adversely impact its coastal areas. The impacts of these storm events will be exacerbated by climate induced SLR and the projected changes to coastal processes. There is a need to better understand these processes social, economic, environmental value, and how much they are at risk from current and future climate impacts. In considering the costs associated with implementing coastal management options it is important to consider what the partial or total loss of beaches would mean for tourism and recreation, the local property market, beach users and the environment. By better understanding the social, economic and environmental values of our coastline, the coastal manager can more easily determine whether the cost of protecting our coastline outweighs or more particularly what management options are appropriate. It has been argued that the spatial knowledge gap can be addressed by investigating options in a pilot study area (Vonk et al., 2007). In summary, as relatively few coastal managers know about the value and the extent of spatial advancements, a pilot study can offer administrators and decision-makers enough data to make decisions on the benefits of the additional information and knowledge provided (Vonk et al., 2007).

As an agency which must manage land development in peri-urban coastal areas, the BCSC takes an integrated approach to Coastal Flood Risk Management (CFRM). This methodology develops rules and structures for data collection, states the required spatial models and systems, and the resources council needs. The CFRM plan has been developed by the council committee in response to the rapid urban development in the BCSC and the impact on water assets. In an IWM approach, natural assets are considered close to water assets. Clause 56 of the planning scheme provides guidelines on residential land development and encourages stormwater best practices and Water-sensitive Urban Design (WSUD) including the development of wetlands, bio-retention facilities, and rainwater harvesting. The council has encouraged these outcomes where possible without consideration of the wider catchment considerations (Lin et al., 2012).

3.3.3 Future Coasts LiDAR Data Availability

State-wide coastal flood maps showing flooding from possible SLR were released in June 2012 through the State Government's Future Coasts Program. However, the State Government did not introduce a planning control to deal with the issue. Affected property owners were not notified and the maps released by the State Government were drawn at such a scale that individual properties could hardly be recognized. Since then, the Council was provided with the inundation dataset, which allows the information to be used for internal purposes but does not allow opportunities to assess development applications through planning control. It does not allow the information to be communicated to the public in a fair and transparent way.

The Victorian Future Coast LiDAR dataset was accessible for the whole BCSC. This LiDAR dataset is a very useful dataset as it provides a high level of accuracy and reasonable vertical precision. DEM derived from LiDAR data is useful for modelling overland flow, identifying catchment boundaries and for hydrological visualisation.

The VICMAP Elevation Coastal 1 m DEM and 0.5 m contours datasets are captured through the Coordinated Imagery Program (CIP) 2007–09. They have been built from high-resolution LIDAR information and are accessible only in their local projection (GDA 94 MGA Zone 54 or Zone 55) and record designs (normal lattice/grid and ASCII format). The 0.5 m contours describe Victoria's coastal rises as form lines at 0.5 m interval. The 1m DEM has a spatial resolution of 1m and a vertical precision of +/- 10 cm within one sigma and is stored both on a normal lattice and in ASCII format.

As discussed in Section 1.7, while it is acknowledged that the Future Coasts LiDAR data covered a portion of the catchment, including the area covered in the analysis in this thesis covering the coastal zone. This data has been used to develop procedures that can be applied to any coastal zone.

3.3.4 BCSC Coastal Spatial Data Gaps and Limitations

Evaluating the potential effects of climate change involves the examination of the spatial distribution of impacts (both present and future) and how they affect resources and infrastructure of local importance. Climatic change may result in:

- An increase in the recurrence/term of a disaster event or effect—with events occurring more often or persevering for a longer period than previously depending on average atmospheric conditions.
- An increase in the force or extent of a disaster event or effect—with an increase in hazard risk.
- A change in the spatial distribution of disaster events or effects — where they occur in regions that they would typically not occur.

However, the anticipated outcomes of climate change often exhibit the above attributes. For instance, SLR is likely to cause more severe storm surges and floods, and shorter return periods between floods, with floods moving further inland thus changing the spatial distribution of floods.

This change in the spatial and temporal distribution of floods has important implications for this research. Specifically, it is difficult to quantify the changes in the spatial distribution of flood events where they do not follow past patterns. However, modelling the impacts of floods over time will allow adjustments to be made to future projections. Therefore, the potential limitations and gaps in spatial data for use in the case study area can be summarised as follows:

1. Uncertainty Regarding Future States: While atmospheric models are very useful for understanding the Earth's atmosphere, it is difficult to know how well an atmosphere model predicts future conditions. The models utilized in this report have been assessed for how they perform in imitating the current Australian atmospheric models (CSIRO and BoM, 2007). The biophysical reports produced investigate vulnerability, yet many of the projections depend on assumptions about the future. While there is some consensus on global warming and SLR, the full extent and local variations are uncertain. Such uncertainty also occurs in the Western Port region's socioeconomic and

environmental data. There is also some level of uncertainty in regard to population projections (Pillora, 2011).

2. Challenges in Linking Change and impacts: While this research investigates the connections between climate change and impacts, the results depend on the reliability of input data. This research provides visualisation of the potential flood risk to structures or mortality from flood events. Also, the visualisation allows evaluation of present and future climate effects. The findings in this research give a greater understanding of the potential extent and impacts of climate change

3. Data Quality and Availability: Limitations in the accessibility of information, the scale at which they were gathered, and their quality can present huge difficulties for coastal climate evaluations. Information gaps may emerge due to (i) limitations in information sharing, (ii) poor quality data collection (Hine et al., 2017) technological limitations affecting the quality and precision of data collection, (iv) challenges in evaluating future conditions (see above), and (v) lack of data about a specific element.

One way to address the gaps in data is to implement the LiDAR application of hydrological features extraction. In Table 3.1 below the benefits of this approach are summarised.

Table 3.1: Benefits of LiDAR data information for hydrology analysis

Using hydrological features extraction will allow for:
A. Refined definition of drainage sub-catchments. B. Refined identification of Overland Flow Paths. C. Refined identification of SLR incursion. D. Rationalisation of the existing drainage configuration. E. Clear identification of assets built in Overland Flow Paths. F. Greater ability to test current drainage system capacity. G. Provision of basic improved tools to assist for development planners at a strategic level assess wider drainage requirements. H. Benefits of Implementation of Water Sensitive Urban Design.
The benefits to BCSC for using this approach include:

A. Risk mitigation for damage caused by overland flows, and also a better understanding of the natural flow characteristic in large storm events. B. Assists strategic planners with responsible development, and to better understand flooding risks due to seawater incursion. C. Assessment of the value of existing drainage, i.e. are the pits all working as intended, and a better understanding of the current system capacity. D. Risk assessment and minimization of public and private infrastructure leads to less litigation and greater confidence by the public, which also will lead to fewer customer complaints and better community relationships. E. Understanding of system capacity leads to better development design and an understanding of additional load management techniques. F. Identification of wider catchment requirements leads to a better understanding of the drainage flows outside localized developments, which provides: a better understanding of the requirements of the rural-urban interface and the wider use of WSUD.
The benefits of this current research on a wider scale include:
A. Better floodplain management through a better understanding of the increased urban flows that come with greater impervious areas in urban development. B. Better environmental outcomes through better WSUD applications. A better understanding of SLR due to climate change. C. Better identification of appropriate location for gross litter traps, outfalls, and fittings to inhibit back-flow of seawater into the drainage system. D. Clearer identification of high-risk infrastructure, leading to clearer long-term asset management plans, for infrastructure at risk. E. Better identification and understanding of flooding hot spots. F. Better emergency management planning and response.

3.4 Chapter Summary

In this Chapter, the reasons the BCSC was chosen as the case area was examined. Rapid urban growth and development in the region mean the BCSC is facing pressure to manage greenfield urban developments. This development places pressure on significant assets and infrastructure in the shire, can result in decreased stormwater quality and increased stormwater overflows and related flooding. The case study area includes an important part of Victoria's coastline, and the BCSC and other responsible organizations must follow the strategies, plans, and policies to manage coastal water quality. The BCSC status as a coastal getaway implies that the council is under pressure to manage land use change to provide space for its expanding population.

BCSC is the first coastal council in Victoria to attempt to inform the LSIO flooding and inundation overlays using solely the Future Coasts inundation LiDAR dataset. In the next Chapter, the focus will be on GIS embedded hydrological modelling using LiDAR datasets and derived information to support coastal hazard assessment and coastal flood planning. The focus will be on procedures in the BCSC spatial decision support system to develop coastal flood-risk management.

Chapter 4

4 Floodplain delineation using Arc Hydro models

4.1 Introduction

Chapter 3 explained the reasons why the Bass Coast Shire Council (BCSC) area was chosen as the pilot study area. Chapter 3 introduced why the BCSC area was chosen as the pilot study area. In this Chapter, a pilot study of the procedure for coastal flood-risk management is demonstrated. A consideration of existing GIS and the remote sensing database to support coastal manager better plan for climate change.

Many researchers predict that climate change will have a direct impact on public and private infrastructure in local government communities (Bulkeley and Castán Broto, 2013). Floods are one of the most serious, common and costly natural disasters that residents in the BCSC are exposed to. Local Government decision-makers need to understand the hydrological characteristics of the watershed to make informed and timely decisions. The aim of the pilot study in this Chapter is to identify the overland flow paths, drainage sub-catchments, legal points of discharge (LPD), and previous and impervious surface areas. There is a need to improve the quality of the drainage data to gain an accurate representation of the impacts of flooding on BCSC drainage infrastructure. This will be achieved by utilizing GIS-embedded hydrological modelling within Arc Hydro and System for Automated Geoscientific Analysis GIS (SAGA). LiDAR dataset (Rata et al., 2014) provides an opportunity for enhancing hydrological parameter estimation for coastal flood systems (Zomorrodian, 2012). Typically, drainage catchment areas, overland flow paths, LPD and pervious surfaces were delineated from topographic maps. Whereas, drainage divides and overland flow directions are located by analysing a DEM (Poppenga et al., 2014) or by visually inspecting on-site ground slopes (Monreal et al., 2018).

Within a GIS, hydrological models enable different spatial and environmental data to be integrated including climate, land use and topographic characteristics. This integration offers great value and presents enormous potential benefits to modellers and engineers (Singh and Fiorentino, 2013). Arc Hydro can be defined as a GIS data structure that links hydraulic data

to water resource modelling and decision-making methods (Sheffield et al. 2018). The Arc Hydro information model institutionalizes water information structures with the goal that information can be utilized reliably and effectively to tackle water asset issues at any spatial scale. The System for Automated Geoscientific Analyses (SAGA) can be used to derive the Topographic Wetness Index (TWI), which can be used to monitor rainfall and runoff. The analysis describes the likelihood of an area to be saturated based on the surrounding area's slope and porosity characteristics (Rinderer et al., 2014).

Chapter 4 explains the current knowledge related to integrating GIS with hydrological modelling and multi-source spatial data systems and provides the framework for answering intermediate research questions 1 and 3:

- RQ1 What is the current integration of GIS with hydrological modelling and multi-source spatial data systems?
- RQ3 How can an integrated hydrological and GIS model be used to improve the existing GIS database?

Moreover, Chapter 4 develops a GIS-embedded hydrological model that integrate data from several sources and provides improved information for decision-making. At an appropriate scale, with good quality spatial data and appropriate attributes, it is possible to create a GIS-embedded hydrological model. In the following sections, the analysis of multiple climate change scenarios is presented.

4.2 Linking GIS and Hydrology Models

Recent progress in remote sensing (RS) innovation and software engineering has improved the accessibility of hydrological information and the registration of assets. Hydrological information is useful for many applications (Stewart, 2015). One of the greatest advantages of utilizing RS information for hydrological modelling and checking is its capacity to create data in the geospatial and temporal domains. This is vital for effective model development, validation and application (Kundapura et al., 2018). This aspect stimulated the advancement of

spatially distributed hydrological models, which explicitly consider the spatial data alongside the regular hydro-meteorological information (Soulis et al., 2016). Many hydrological models have been created, such as HS (European Hydrological System) (Abbott, 1986), IHDM (Institute of Hydrology Distributed Model) (Beven et al., 1987), HYDROTEL (Fortintf, 1986), WATFLOOD (Kouwen, 1988), and Japanese models (Tachikawa et al., 1994). The utilization of hydrological models and RS data requires powerful and easy data processing software and hardware.

GIS has proved to be very useful for managing both raster and vector data and handling many points. GIS enables overlaying, merging and visualizing of the geo-referenced data. These are key tasks that simplify distributed hydrological modelling. There is, however, a problem in simulating hydrological processes at a time scale shorter than that of the surface water process observational time scale (Allan, 2018). At shorter time scales, the connection of GIS and hydrological models becomes difficult because the simulation of channel flow depends heavily on the construction of the channel network. Processing cannot be done cell by cell. Physically, the channel flows are only from upstream to downstream, and a channel flow plan is required which considers the structure of the channel arrangements. One of the reasons for this investigation is to develop a spatially distributed hydrological model and construct a modelling system using this method. This system will allow closer connections between GIS and hydrological models.

4.2.1 Embedding Hydrological Functions in GIS

The recent trend in hydrological modelling is to incorporate spatial datasets and representations with complex computational routines. As hydrological modelling abilities have developed, its use with a GIS has resulted in advancements. It helps information capture and provides extra tools for investigation (Zhang and Pan, 2014a). This mix of GIS innovation and hydrological analysis has resulted in incredible progress, particularly for modellers and specialists. There are some enhancements to GIS that utilize the hydrological examination capacities to extract hydrological data, derive surface streams and model drainage flow from a DEM. For instance, ArcGIS 10.x has many hydrologic analysis functions. One can benefit from these additional capabilities embedded within GIS environment. However, where the hydrological models

cover large areas, developing hydrological frameworks is more challenging. Arc Hydro has strong capabilities for the three-dimensional ordering of spatial cells (Soman et al., 2018), and offers a novel method to coordinate GIS and hydrological models. One can fully avail these functions provided by GIS software, but most of the hydrological modules suffer from severe limitations to the capability of modelling a complex hydrological system.

As the need for the development of hydrological modelling capabilities has evolved, its integration with a GIS has provided a significant contribution. It serves the role of providing support in data capturing and additional tools for effective analysis (Zhang and Pan, 2014b). This combination of GIS technology and hydrological modelling has delivered great value and opened multiple opportunities for potential benefits to modellers and engineers. Arc Hydro data model has useful functions, like the three-dimensional indexing of spatial features.

4.2.2 Hydrological Analysis Using SAGA

Hydrological analysis focusing on soil wetness is the first step in examining where flood-prone areas in the watershed are found. For this reason, two programming bundles—Quantum GIS (QGIS) and System for Automated Geoscientific Analyses GIS (SAGA GIS), are utilized. The two GIS packages are readily accessible and easy to understand. The LiDAR DEM was used in the SAGA-GIS package in the R-platform to produce a wetness index for each grid cell. Different approaches such as fill sinks; calculation of the slope of each grid, matrix, and catchment zone were assessed to create a wetness index (Wu et al., 2016).

The management of flood-prone areas at a local scale depends on the Topographic Wetness Index (TWI) approach and its variation, the SAGA TWI. The TWI is a strategy used to integrate and visualise precipitation and runoff. The suitability of an area to be developed depends on the surrounding area's slope characteristics and permeability of the ground surface as depicted in the study (Olaya and Conrad, 2009).

TWI was proposed by Beven et al. (1987) as the topographic wetness index (TWI) and is related to (upslope) stream collection area (or drainage area, a) and slope gradient β as follows:

twi = ln(a/tan(B) (Gallant, 2000) and the point of the incline. TWI has been utilized for a wide range of applications (Moore et al., 1991, Quinn et al., 1995, Sørensen and Seibert, 2007).

Although TWI expects the soil in the watershed to be isotropic and homogeneous, it has been discovered that geographical changes in the watershed are substantially more important. TWI has been utilized in the hydrological investigation of this examination. The SAGA TWI utilized in SAGA GIS depends on a changed values catchment area calculation. For cells arranged in valley floors with a little vertical separation to a channel, it provides a reasonable indication of flood susceptibility, with higher potential soil dampness when contrasted with TWI. This methodology means a more extensive region can be affected by water from flooding.

4.3 Methodology

4.3.1 Data and Software Requirements

A small number of freely available software packages are accessible online for landscape analysis. This research utilized the ESRI ArcGIS and Spatial Analyst based tool *'Arc Hydro'*. Arc Hydro is a very useful GIS package and toolbox created at the Centre for Research in Water Resources at the University of Texas in Austin. The toolbox is accessible on the web and is also utilized by SAGA. The information required to conduct the examination mentioned in this exploration include:

- Vector polyline data of the pipe and stream networks.
- Vector polygons data of parcel boundaries.
- Aerial photographs

The method for creating accurate overland flow model from high-resolution LiDAR Data involves firstly creating a TIN surface from LiDAR ground point data. One way to remove spurious sinks in ArcHydro is to use 'Fill Sinks' but a better method is to remove the sinks using SAGA. Surface depressions are removed, and a depression filling algorithm developed by Wang and Liu (2006) is used. The method was developed to allow the creation of a hydrologic sound elevation model, i.e. preserving the downhill slope along the flow path.

Once basins were filled, the flow direction was calculated using the adjusted DEM values and the eight-way pour path model and the steep flow path algorithm. The next step was to calculate

the water flow rate, which was used for specifying the stream links in the next step. Using AcrHydro, overland flow paths start at the point where the accumulation exceeds the threshold. Stream definition conversation defines a default marginal set of ten percent of the total sewage area, which may be too detailed or too general for larger study areas. However, processing of larger DEM files using smaller threshold values may require an extended processing time for completion.

For this study, five percent of the sewage area was set up. The stream level output was in binary raster format. The stream cells are attributed with 1. Subsequently, the stream grid was subdivided into representative segments between confluences, with each segment being assigned a unique grid code identifier. In the next step, the result link grid was used to create a catchment grid based on the values of each stream category. As defined in the previous step, the number of catchments was equal to the number of stream segments. In the next step, these catchment grids were converted to polygon vector features with single cell catchments automatically dissolved. Also, the link grid from the previous processing was converted to a line feature class using the line-processing tool. Figure 4-1 shows the entire process involved in the hydrology model using ArcHydro extension in both ArcGIS 10.x and SAGA.

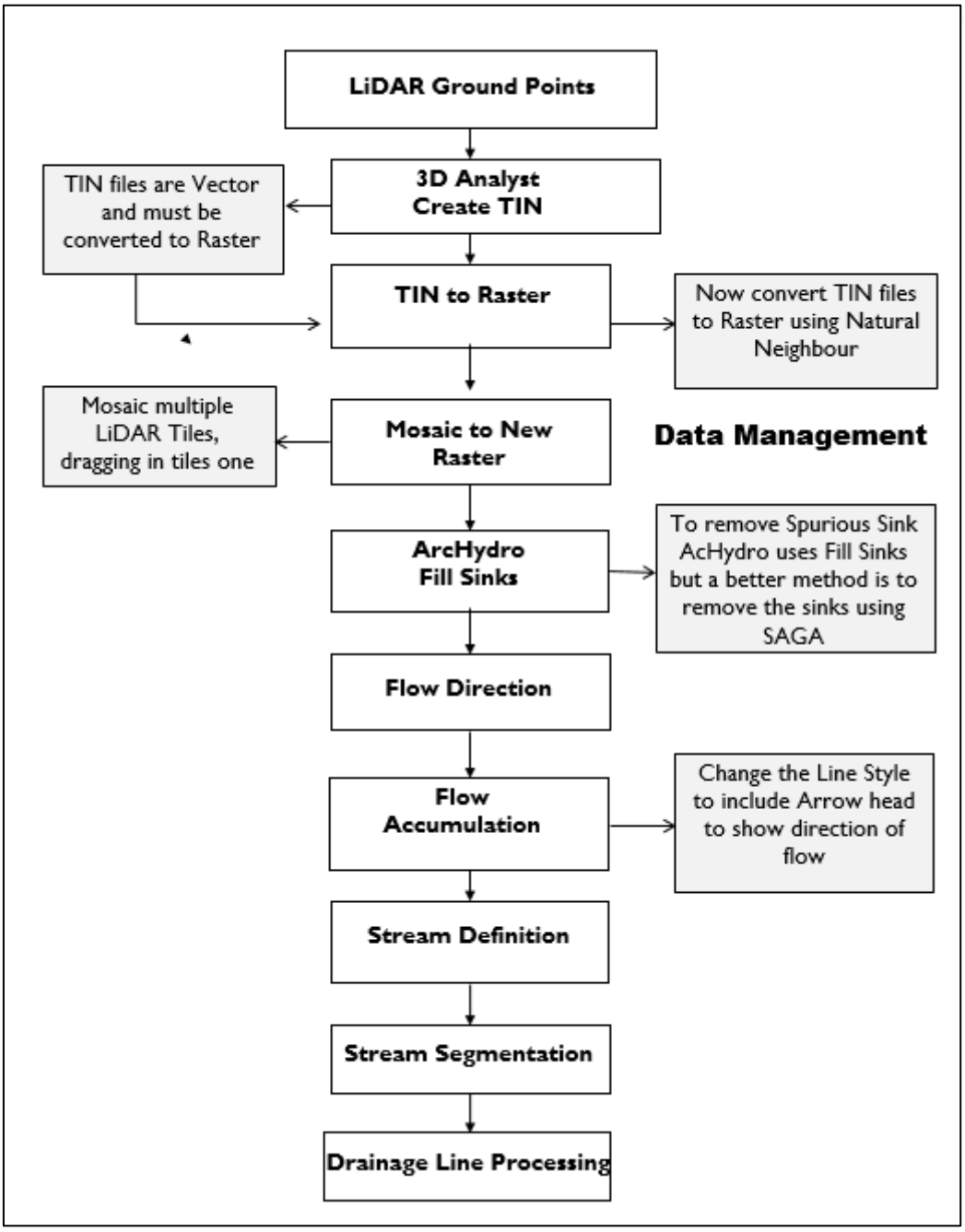


Figure 4-1: Flowchart showing methodology

4.3.2 Digital Elevation Models

Water resource management usually requires examination of landscape and hydrological features such as drainage networks, slope, drainage divides and catchment boundaries (Liu et al., 2005b). Generally, these features are acquired from topographic maps, field reviews and

photogrammetry that can yield high-accuracy landscape information (Garbrecht and Martz, 2000, Liu and Wang, 2008). However, these techniques are labour-intensive, time-consuming and error-prone (Dadson et al., 2003, Liu and Wang, 2008). In addition, in certain circumstances, for instance, in forested zones, it is difficult to utilize these strategies for gathering elevation data (McDougall et al., 2008). Digital Terrain Models (DTM) or Digital Elevation Models (Poppenga et al., 2014) are digital representations of ground levels at each node of a fixed regular grid and terrain-related application (Liu et al., 2005a).

The most commonly used DEMs in Australia and globally were typically produced by using elevation data derived from existing contour maps at varying scales ranging from 1:25,000 to 1:100,000. Later on, digital stereo capture was been used, providing a terrain surface representation with a horizontal resolution of 20 to 50 meters (Vaze and Teng, 2007). Now, more and more high quality DEMs are generated photogrammetrically from a wide range of remotely sensed data sets (Noh et al., 2015). In Victoria, the framework DEM data is held by the Land Use Victoria, Department of Environment, Land, Water and Planning. This DEM, known as Vicmap Elevation, was created under the Victoria Geospatial Information Strategy 2000–2003 (VGIS), (Liu et al., 2005). The source of elevation datasets includes contours, ground points and slope profile break lines (Land Victoria, 2002). In the Vicmap Elevation Coastal 1m DEM & 0.5m Contours dataset, the 0.5m Contours represents Victoria's coastal elevations in the form of contour lines at 0.5m intervals. Although these are great beginning datasets, DEMs produced from these have significant errors due to the size of the original maps used to create them and digitizing errors (Vaze and Teng, 2007).

LiDAR information can achieve a precision of 15 cm root mean square error (RMSE) in the vertical and 20 cm RMSE in the horizontal (Ravi et al., 2018). It offers numerous advantages over customary techniques for describing a landscape surface. The benefits include accuracy and cost (Liu and Zhang, 2008, Liu et al., 2005). One of the most attractive characteristics of LiDAR is the very high vertical accuracy which enables the Earth’s surface to be represented at high accuracy (Ma et al., 2014). The three-dimensional nature of this point model is one of the useful features of LiDAR (Habib et al., 2005). Because of LiDAR's shorter wavelengths in the electromagnetic spectrum, it is able to map of the underlying topography below forests,

addressing the impediments of photogrammetry in forested zones (McDougall et al., 2008). Also, in contrast to the photogrammetry approach to DEM generation, LiDAR is less dependent on the weather, season and time of the day in data collection (Sampath and Shan, 2007). LiDAR is utilized for a wide range of applications, for example, building extraction (Huang et al., 2019), 3D urban visualisation, hydrological modelling, ice sheet observations, landform or soil characterization and waterway banks (Clark and Walder, 1994). It is used by coastal managers and woodland boards (McDougall et al., 2008). However, landscape modelling and visualisation has been the essential focal point of most LiDAR gathering missions (Hodgson et al., 2005). Due to the complexity of urban areas as a result of the presence of small-scale features like roads and buildings (Haile and Rientjes, 2005), high-resolution DEMs are an important way to represent the terrain.

The best results for DEM generation of the natural surface are achieved through extracting it from LiDAR data (McDougall et al., 2008). Almost all of the applications, including water resource management and hydrological modelling, require high-quality DEMs because the accuracy of DEMs directly affects the accuracy of hydrological predictions (Tuteja et al., 2007). Thus, LiDAR information is relevant to water assets and hydrological modelling. (Liu et al., 2005b) recommended that LiDAR be used for DEM depiction of sub-catchments as LiDAR DEM provides the required spatial resolution.

The point-cloud approach to DEM building is based on a raster data model. This means that it uses rectangles as the fundamental units within the raster array and the hydrologic characteristics are uniform within each grid cell (Sample et al., 2001). This grid DEM utilizes a lattice structure which records topological relations between the point-based measurements (El-Sheimy et al., 2005). The grid DEM is simple to use and is the most efficient method of storage and manipulation because its data structure is similar to the array storage structure in a computer (El-Sheimy et al., 2005, Erskine et al., 2006).

The results from the statistical analysis conducted by Vaze and Teng (2007) indicate that the 1m LiDAR DEM offers a representation of the ground elevations that is adequate for detailed hydraulic and hydrological modelling exercise for most terrains. High-resolution DEMs are

increasingly being made available through a number of public and commercial providers (Di Luzio et al., 2004). Some are from the application of digital photogrammetry and some are derived from processing of LiDAR data.

DEMs are especially useful in providing a detailed representation of flow paths (Gupta et al., 1980). Catchments and stream flows can also be modelled from DEMs. However, they should be changed to recognise the impact of buildings, infrastructure and irrigation systems. Previously the utilization of DEMs in distributed hydrological modelling was confined to catchments lacking built-up areas (L'homme, 2004). Consequently, only recently have DEMs been used for modelling built-up catchments (Wheeler et al., 2008).

To yield more accurate hydrologic basin models than traditional approaches, DEMs are utilized in delineating water catchment boundaries and extracting other elements of a drainage network, such as flow path and drainage density (Cápiro et al., 2007). Other elements of hydrology, for example, flow direction, flow accumulation, flow length, stream networks and drainage areas can be determined using standard functions from commercially available GIS software that works on raster surface information.

Raster-based DEMs also appear to be a suitable terrain model for displaying gravity-driven streams as flow directions are dependent on topography and not on pedologic secondary variables (Olivera and Maidment, 1999).

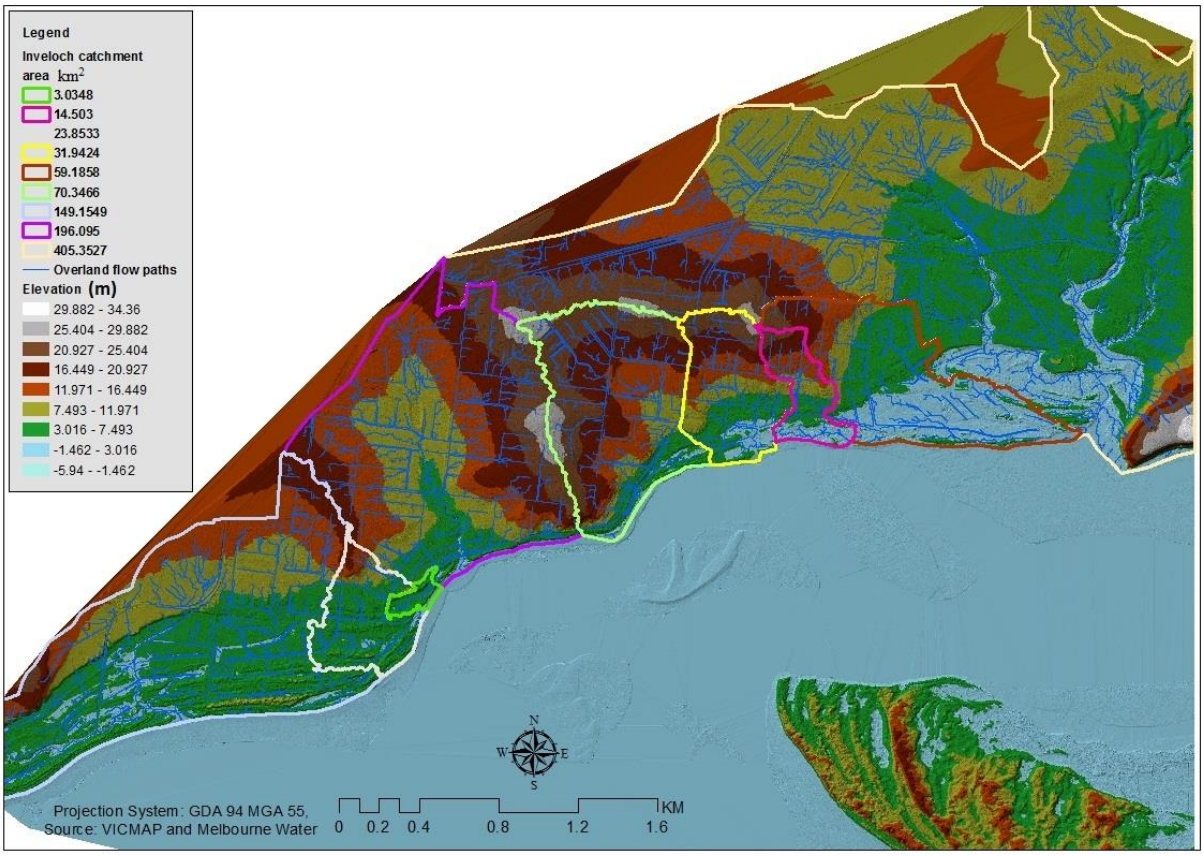


Figure 4-2: Comprehensive hydrological DEM Inverloch area developed from LiDAR.

Therefore, without dense LiDAR information, it is impractical to produce a correct drainage network model and the subsequent catchments. LiDAR provides an opportunity to identify overland streams with increased accuracy, resulting in the improved interpretation of the direction of water flow across the catchments. BCSC data initially had only 10 meter contours that do not provide sufficient resolution to run Hydrology models to establish accurate overland flow patterns on a large scale. Contours of 0.5m from LiDAR data provide the opportunity to find solutions to a whole host of problems - not just single-level flows, but multiple 2D flows.

To unlock these benefits this research created customized tools to ensure quality, represent forms, reduce errors, increase confidence in GIS information and streamline the work process for error correction. This has helped the council GIS team to reduce and rectify mistakes and data errors by improved quality assurance and deliver better strategic decision-making tools.

4.4 LiDAR Modelling of Overland Flow Path

Overland flow path identification and catchments delineation are fundamental tasks for stormwater modelling. However, manual procedures can be very tedious. This section presents two unique techniques for computerized modelling of catchments and streamflow. The use of GIS-based methodologies for catchment delineation and flow path identification for urban hydrological modelling are also discussed.

This study explores urban overland flows and stormwater drainage system utilizing grid-based GIS techniques and traditional (manual) approach. The accessibility of LiDAR datasets has resulted in more accurate DEMs of urban. A significant part of the text shown below has been derived from ESRI manuals. Features such as streets, kerbs and structures significantly affect catchment performance and overland flows and must be represented in the model. This is possible by means of high-resolution DEMs. The first step in urban hydrologic modelling of urban stormwater systems include delineating the catchments and identifying overland flow paths. Advances in LiDAR data processing tools and GIS functions have improved hydrological modelling for urban areas. The DEM is the foundation of the data analysis and care should be taken during its preparation. Creation of an inaccurate DEM will almost certainly produce erroneous results. ArcGIS geoprocessing tool (Topo-to-Raster) that interpolates a hydrologically correct computerized rise model (i.e. DEM's). The theory of how the DEM is computed is outside the scope of this research and isn't mentioned here. While ArcGIS Spatial Analyst was used in this research, other options exist such as Global Mapper (Kristina, 2004).

4.4.1 Converting from TIN to GRID and Terrain Processing

Only terrain that is characterized in raster form (Reidsma et al., 2011) can be used in this type of hydrological study. Triangulated irregular network (TIN) information can be helpful and gives accurate 3D terrain models from datasets such as LiDAR. However, erroneous results from low-resolution contours, particularly in flood areas, might be produced. It is not advisable to alter TIN information so that water will flow downhill and subsequently it is not utilized in the hydrological analysis. As mentioned above, Topo-to-Raster Arc hydro is very suited to use

with hydrological DEM's where there is a dense point distribution LiDAR created from 0.25m contour data. Since raster DEM's are required for detailed hydrological modelling, TIN won't be mentioned further. In any case, it ought to be noted that a TIN can be helpful for extensive catchments, as Topo-to-Raster has a limitation of approximately two gigabytes or 6500 x 6500 cells (around 4250 ha with a 1 m network separation). In these cases, TIN's can be made and converted to a raster design for use in hydrological modelling. There have been upgrades in ESRI ArcGIS 10 to update the capacity of Topo-to-Raster, and the most recent Arc Hydro can create matrices of virtually unlimited size.

When using a hydrologically sound DEM, the flow direction and flow accumulation grids, frequently require refinement through drainage flow calculations. To understand the flow of water through the watershed, the hydrologically adjusted DEM must have the best possible accuracy to model the subtleties of overland flows. Issues frequently emerge when the data resolution is not fine enough. The following steps were utilized to acquire a hydrologically sound DEM that was utilized to delineate catchments and identify streamflow paths for an urban catchment in the Inverloch area.

4.4.2 DEM Reconditioning and Filling Sinks

When the flow definition is finished it is essential to carefully analyse the derived flows and ensure that flows are correct. Commonly, where the flow delineation most often failed was where the flow met streets, and in flat areas. These errors can cause numerous issues in the catchment delineation and flow path identification and need to be rectified by reconditioning the DEM.

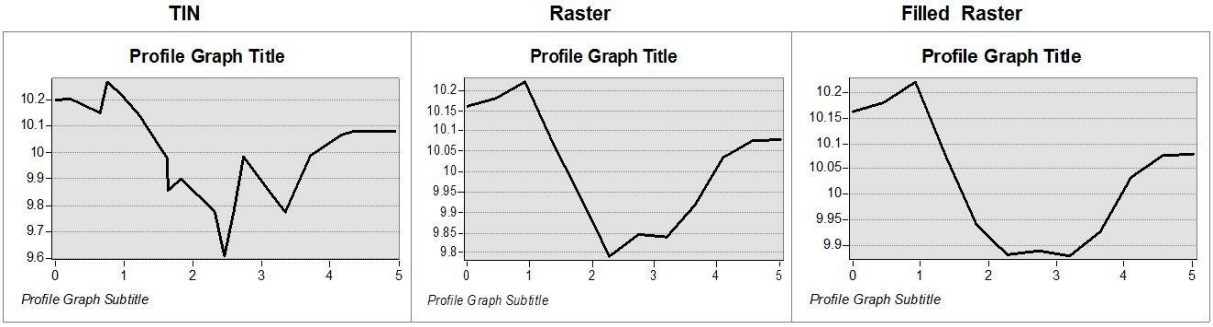


Figure 4-3: Reconditioning the DEM and using the "Interpolate Line and Create Profile Graph" tools to examine a cross-section profile across a stream

The decision to recondition the DEM needs to be made with the proposed DEM use in mind. In urban modelling a reconditioned DEM is required for catchment delineation for overland flow path generation an unconditioned DEM will also have its advantages. As seen in Figure 4-3 the stream extraction from the unconditioned DEM accurately portrays what would happen when the culvert overflowed. This type of analysis is very useful in overland flow determination; however, it can produce incorrect results in catchment delineation. The unconditioned DEM's were found better for identifying overland flow paths at roadways and stream blockages.

Reconditioning the DEM modifies the DEM by imposing line features (corrected flows) onto it (sometimes referred to as burning and fencing). DEMs were implemented using the AGREE method developed at the Centre for Research in Water Resources at the University of Texas in Austin (Merwade, 2018). The algorithm requires a raw DEM (or filled DEM) and a vector polyline.

What 'AgreeDEM' (or DEM reconditioning) does is modifies the raw DEM along the stream to create a distinct profile which otherwise does not exist in the raw DEM. This was mainly utilized when the stream is piped under roadways or where there was inaccurate or missing elevation data along the streams due to heavy bush cover. Once the reconditioned DEM was produced the process was repeated until an acceptable flow definition grid was achieved. Additionally, it was also useful to keep the unconditioned filled and flow direction grid for overland flow path delineation.

A series of steps are used to delineate watersheds or define flow networks. While some steps are required, others are optional depending on the characteristics of the input data. Flow across a surface will always be in the steepest downslope direction. Once the direction of flow out of each cell is known, it is possible to determine which and how many cells flow into any given cell. This information can be used to define watershed boundaries and flow networks.

A sinkhole is a cell where water does not have a natural drainage pour point - that is no cells surrounding it are lower. If a cell is surrounded by cells with higher elevation, the water is caught in that cell without a natural point of discharge (Maathuis and Wang, 2006).

A farm dam that is at capacity and has an exit point where the water flows out was treated as a "Sink" and given the same exit value as the entry value. A genuine sink is a place where the water flows in and not out as in a glacial lake, basin or depression.

This is useful for minor fill areas and vast fill zones as illustrated in Figure 4-4 below. It will be enlarged by reconditioning the DEM to keep the correct flow course. The fill framework is good at anticipating potential flooding areas. Nevertheless, one must be mindful that flooding areas can be distorted by an inaccurate representation of the topography. The detailed methodology of filling sinks is discussed below section 4.4.7 (Jenson and Dominguez, 1988).

4.4.3 Flow Direction and Flow Accumulation

One of the keys to deriving the hydrologic attributes of a surface is the capacity to decide the flow direction of flow from each cell in the raster. This is accomplished with the streamflow determination process.

This process accepts a surface as information and yields a raster-based modelling of the flow direction of the flow out of each cell. If the "output drop raster" alternative is picked, an output raster is made. This output raster is the ratio of the maximum changes in height from every cell along the course of the overland flow path and the focuses of cells and is expressed as a percentage.

There are eight flow directions related to the eight neighbouring cells into which flows could travel. This methodology is ordinarily called an eight-course (D8) flow display and pursues a methodology displayed in (Ali, 2018). The flow direction grid was derived from the filled DEM because the water flows downhill and will follow the steepest slope. The flow direction gird is encoded 1 for the east, 2 for the south-east, 4 for the south, etc. to 128 for upper east as appears in Figure 4-4 below. The flow direction grid is the core grid utilized in catchment and overland flow delineation.

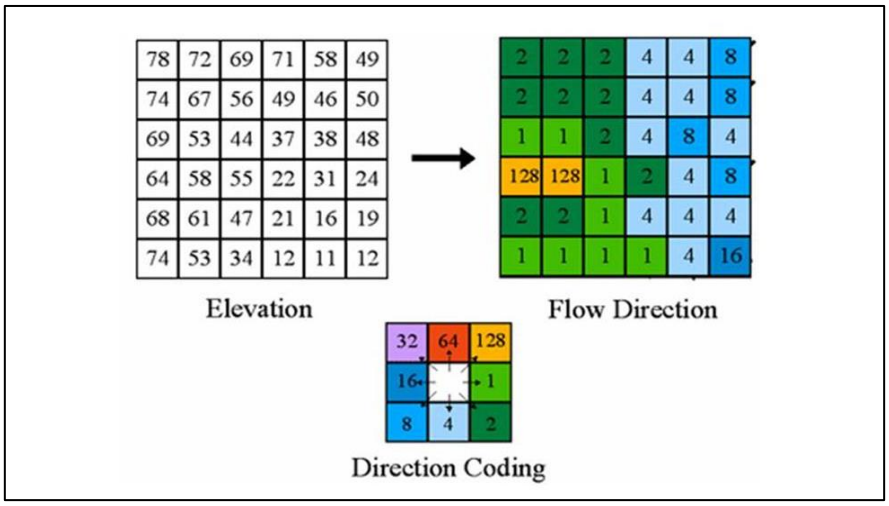


Figure 4-4: Example of flow direction grids that use the pour point in eight directions *(Keenan et al., 2011).*

The flow accumulation grid records the number of cells flowing into each downslope cell in the output raster. If no weight raster is given, a weight of one is applied to every cell, and the estimation of cells in the output raster is the number of cells that flow into every cell. In the example above (Figure 4-4), the upper left picture demonstrates the course of movement from every cell and the upper right shows the number of cells that flow into every cell.

Cells with a high flow volume (i.e. larger number of in-flow cells) are zones of concentrated flows and might be utilized to distinguish flow channels. The flow accumulation network was determined from the flow direction lattice. The flow accumulation grid is the core grid used for defining stream network.

4.4.4 **Flow accumulation after fill sink**

Figure 4-5: Example of regions where sinks were filled during the underlying flow accumulation process (Screw Creek, an example of a Sink shown here in blue)

"Filling sinks" involves filling the sinks in an elevation matrix. Where cells with higher elevation surround a cell, the water is caught in that cell and can't flow out. The Fill-Sink operation adjusts the elevation to address these issues.

DEM can be used to determine flow directions for each location. If there are errors in the elevation shown or if you are modelling karst sinkholes or caves, there might be some cell areas that are lower than the surrounding cells. If so, all the water going into that cell will not escape. The hydrologic analyses tools find the sinks and give tools to fill them. The result is a depression-less height model which allows the flow direction to be determined on this depression-less height model.

When delineating watersheds, pour points (areas for which the contributing watershed is required) should be identified. Commonly, these areas are mouths of streams or other hydrologic focal points, for example, a gauging station. Utilizing the hydrologic analysis tools

indicates the pour points or the stream flow as the pour focuses. This provides watersheds for each flow portion between the flow intersections. To model, the streamflow should initially be calculated for every cell. To define flow linkages, we need to understand the direction of stormwater flows from cell to cell. How much water pours through a cell, or what number of cells flow into another cell is needed?

4.4.5 Stream Definition and Stream Segmentation

With the flow accumulation grid, streams were defined using a threshold drainage area. The threshold area is the area (number of cells) that must be accumulated before cells will be labelled as a stream path. This result in a raster grid where 1 signifies a stream path. From this grid, a polyline feature class can be derived to represent the stream network for the defined threshold.

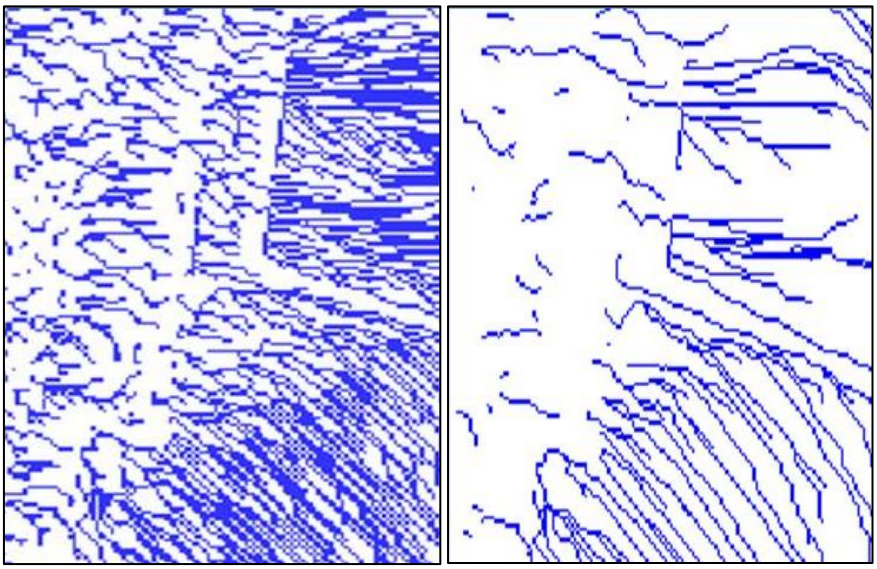


Figure 4-6: Stream definition with a small threshold (left: flow accumulation = 10) or a large threshold (right: flow accumulation = 105).

As can be seen from Figure 4-6 the default value is shown for the creek threshold. This result shows 1% to be the most extreme flow accumulation. The maximum drainage region to produce a stream is then 3601 x 100 x 100/1000000 = 36 km^2. In any case, some other estimation of the edge can be chosen. For instance, the USGS Elevation Derivatives for National Applications (EDNA http://edna.usgs.gov/) approach utilizes an edge of 5000 x 30

x 30 m cells (a territory of 4.5 km^2) for catchment definition. A smaller threshold value results in denser stream flow and the larger number of catchments. Objective methods for the selection of the stream definition threshold to derive the highest resolution network consistent with geomorphological river network properties have been developed and implemented in the TauDEM software (Bowen et al., 2018).

Stream segmentation involves the identification of stream sections and junctions. Either a segment might be ahead connection, or it might be defined as a segment between two segment junctions. Cells in a specific segment have a similar grid code that is specific to that segment. Next stapes grid delineation creates a grid in which each cell carries a value (grid code) representing to which catchment the cell belongs. The value links to that carried by the stream segment that drains that area, defined by the stream segment link grid.

4.4.6 Catchment line and polygon Processing

Three processes - Catchment Polygon Processing, Drainage Line Processing and Adjoint Catchment Processing - convert raster data developed so far to a vector format. The component dataset made by catchment polygon processing purportedly acquires the degree from the best layer in the ArcMap archive. This capacity changes over a catchment network into catchment polygons. Every catchment additionally has shape, length and area characteristics. These amounts are naturally processed when the feature class is part of a geodatabase

The adjoining catchment processing function generates the accumulated upstream catchments from the "Catchment" class. For every catchment that isn't a head catchment, a polygon representing the entire upstream zone draining to its inlet point is developed and stored in a feature class that has an “Adjoin Catchment " tag. This component class speeds up the point delineation process.

The discussion up to this point has concentrated on the drainage area preparation techniques that are well established in watershed modelling. These devices and techniques have proven

helpful in the watershed analysis. The remainder of this section discusses how automated catchment delineation approaches can be used for detailed urban catchment modelling.

The watershed method utilizes the flow direction and flow accumulation to outline catchment limits. Utilizing the watershed method to create urban catchments is different to the other techniques. This is because most other recognised approaches are intended for catchment delineation in substantially open watersheds utilizing streams as the outfall system. For urban catchments, a polyline vector dataset of all the channels (displayed and un-demonstrated) and open conduits were utilized to outline catchments. Open waterways are spatially correct, and this is recognised in the reconditioned DEM investigation. The system features, including open waterways, were converted to a solitary raster lattice with a network number code with a component ID. Consolidation of un-demonstrated and short connections was utilized as each connection with a special component ID gets a one catchment limit. Figure 4-7 shows how the reconditioned DEM was used to show catchments or drainage basin outlines.

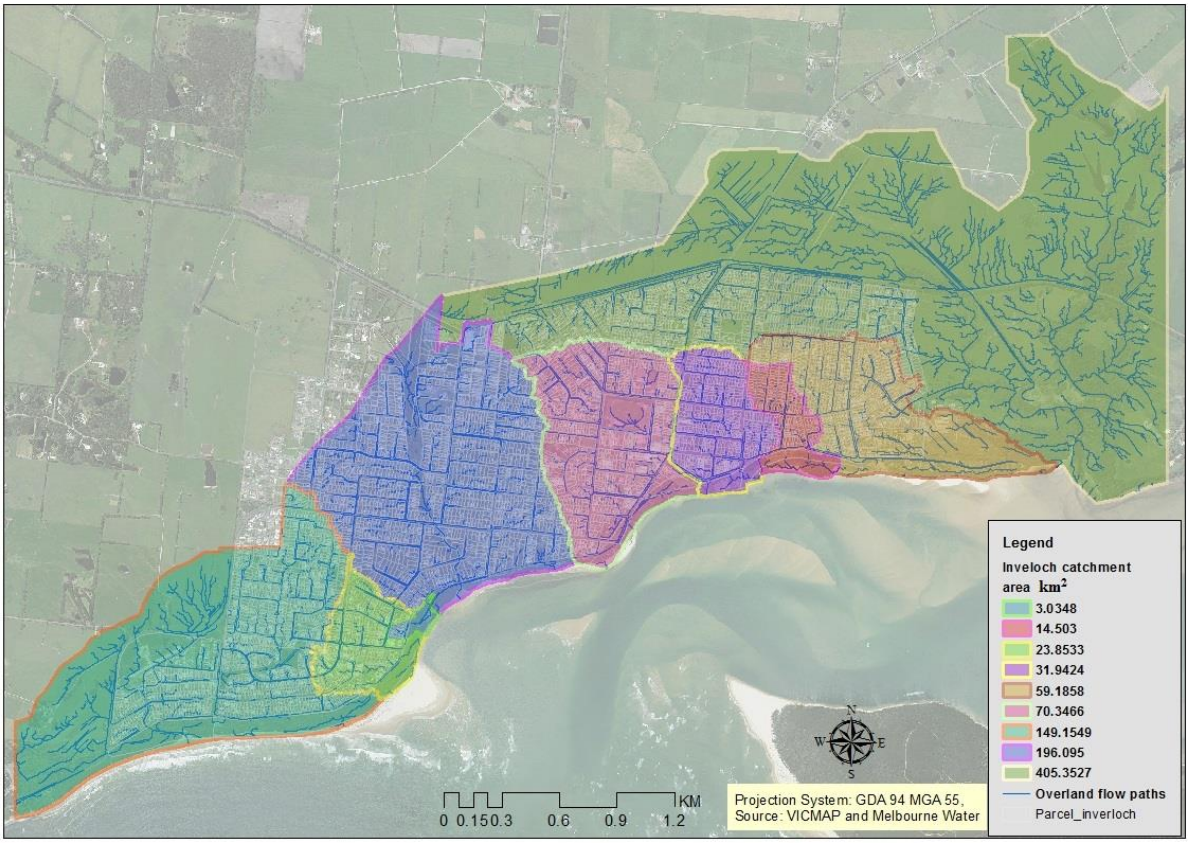


Figure 4-7: BCSC drainage basins and overland flow path

The catchment outline is stored in a catchment network, with estimations of every cell connected to the component Id to which its channels. The catchment framework would then be able to be changed to a polygon vector record and connected back to channel hubs by means of the pipe id. Catchments were balanced and wrong polygons converged trying to "clean" the catchment record. Similarly, a balance is needed between pre-handling DEM reconditioning, stream delineation, and system interface combining), and post-handling "cleaning".

The watershed method in urban catchments has proven to be a very useful tool for automating catchment delineation in stormwater and combined systems (Chen and Tucker, 2003). However, this technique has been used in sewer systems with less success. This is because the watershed method is very dependent on the flow direction and ultimately the flow accumulation grid. Often, drainage channels are not placed in low lying areas of the catchment, which results in unpredictable flow accumulation along these channels and difficult catchment delineation.

Instead of connecting the node points, using this system has proven to be an appropriate technique for catchment outline in urban areas since it enables more cells to accumulate flow. This is essential where joins are along streets with very small drainage areas or on slopes.

4.4.7 **The Theissen Polygon Method**

Theissen polygons are polygons whose boundaries define the area that is nearest to each point relative to all other points. This method is used to delineate catchments in a sewer catchment (Colombo et al., 2001). The method uses a double sweep Theissen closeness calculation to dissolve parcel borders and road assets based on their proximity to the sewer network (See Figure 4-8). All connections in the sewer system can be utilized to get a “proximity” catchment for each connection in the system.

In the main range, all parcel borders are joined using the closest connection and then dissolved based on the ‘connection id’. Secondly, street reserves are divided and dissolved into each catchment limit by using a second proximity analysis on the dissolved parcel boundaries. This results in a topologically correct polygon vector file that is associated with each identified network link. The catchments depend on the package limits and road reserve proximity to the related connection. Land use and census grids can then be used to determine population and land use. As with the watershed method, this research found that the utilization of the connections, as opposed to hubs, creates the best outcomes in the proximity analysis.

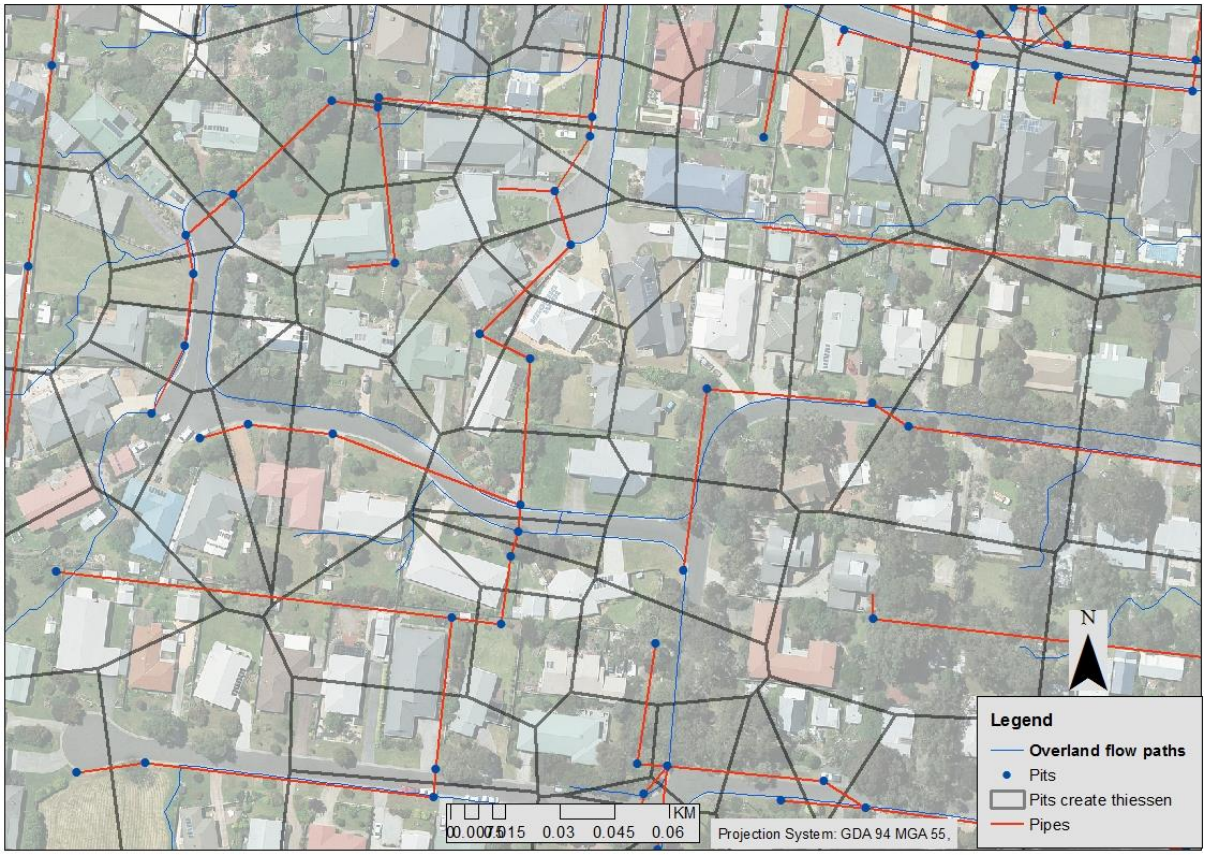


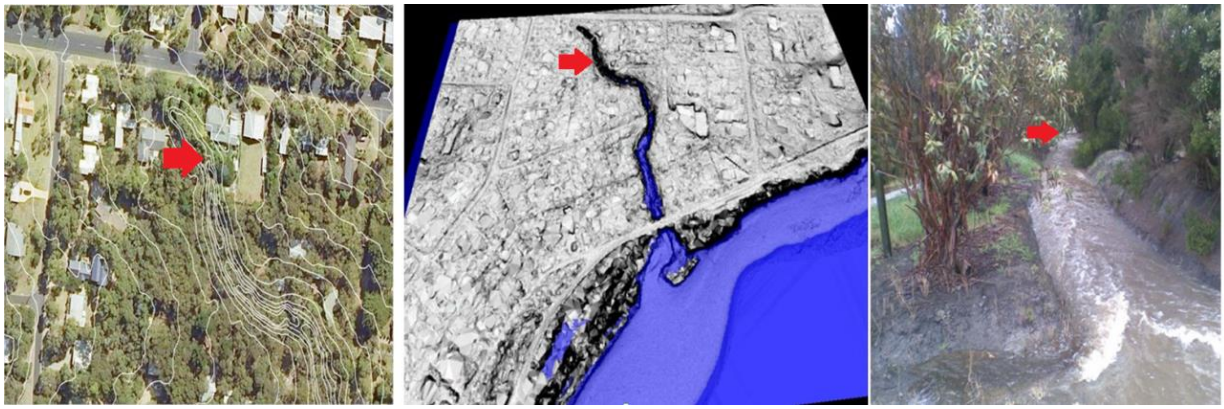
Figure 4-8: Example of detailed delineation of the basins using the two- sweep method Thiessen polygon BCSC.

4.5 LiDAR Generation of Flow Direction Networks

Overland flow is the movement of water over the ground segment of a drainage system. Overland flow occurs in urban areas when the underground drainage system achieves its capacity and can't adapt to more inflow, ordinarily because of overwhelming precipitation. The excess run-off then travels overland, along low-lying, natural drainage paths. Generally, tracing the overland flow was a very time-consuming procedure, particularly with stormwater. Programming of this overland flow fundamentally speeds this procedure and produces a substantially more precise portrayal of an overland stream. The data on overland streamflow is helpful in sewer models to survey the natural impact of uncontrolled floods. Automated flow path generation provides information on where the node point will be.

Figure 4-9: Inverloch overland flow path

As illustrated in Figure 4-10, the result is a definition of the overland flow paths (in this case in Inverloch). This is very useful for council and Inverloch residents in making decisions about land use and development.



A: Ayr Creek contour ***B: Ayr Creek DEM*** ***C: Ary Creek flood***

Figure 4-10: The LiDAR data reveals the location of a critical watercourse

Previously Council only had access to 10‘-metre’ contour information which was inadequate for the precise identification of overland flow path. At the strategic level, it is essential that local government access high-resolution elevation data to identify the intricate changes of grade that affect overland water flows, and this will also enable us to better design roads and drainage. GIS and LiDAR data make it easy to generate contour lines with a 0.5-metre elevation interval from digital elevation models.

DEMs can also be displayed in 3D and used as a surface to drape other layers and images in 3D when utilizing software such as ArcScene. DEM used in this study is based on LiDAR models, not on actual surveys. Coastal protection efforts may prevent some low-lying areas from being flooded as SLR. The 0.25-meter contour shown is currently about 1.0-metre above mean sea level (See Figure 4-11). Therefore, some of the areas depicted in blue will be above mean sea level for at least 70, and probably 100, years.

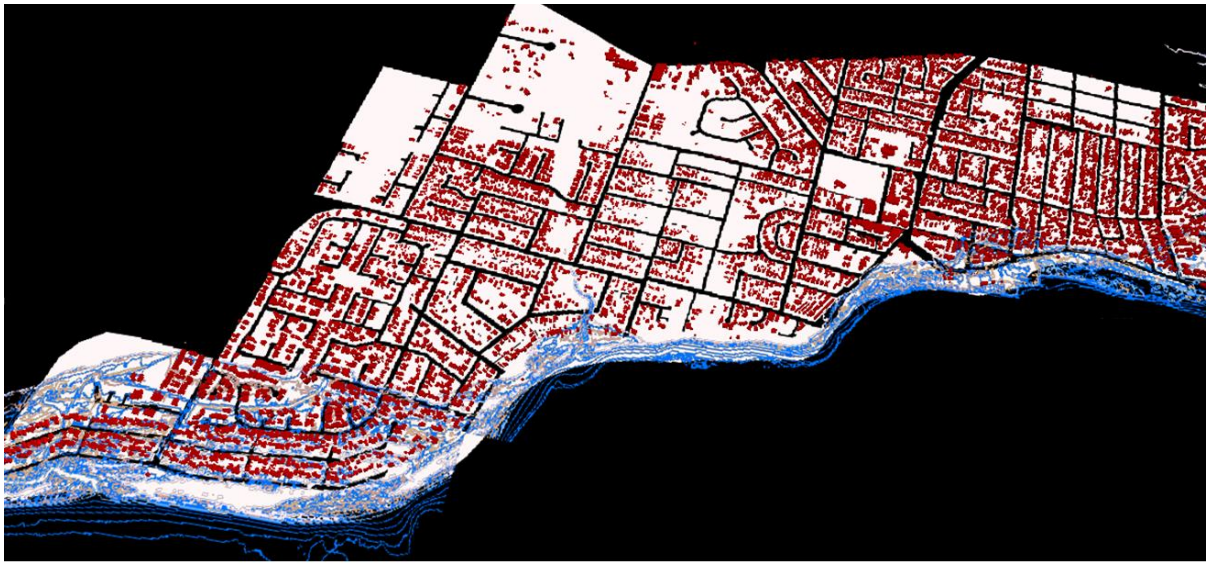


Figure 4-11: Blue colour line 2 m Elevation, 3D building visualization, Inverloch area.

The blue lines in Figure 4-11 show the 0.25m contour in relation to infrastructure and buildings. These results are then presented in Figure 4-12 below at a larger scale. In Figure 4-12 the yellow circle includes 4 pits (shown as red) with drainage problems, which causes problems in overland flow (shown as blue a blue). This is an example of the complexity of hydrological models being more complex in urban areas.

Hydrological analysis of this kind is rarely performed as an integral part of practical urban planning. These hydrological models are often very complex and data-intensive and hence they are beyond what a local planner could manage in terms of time. In addition, such modelling and analyses are expensive.

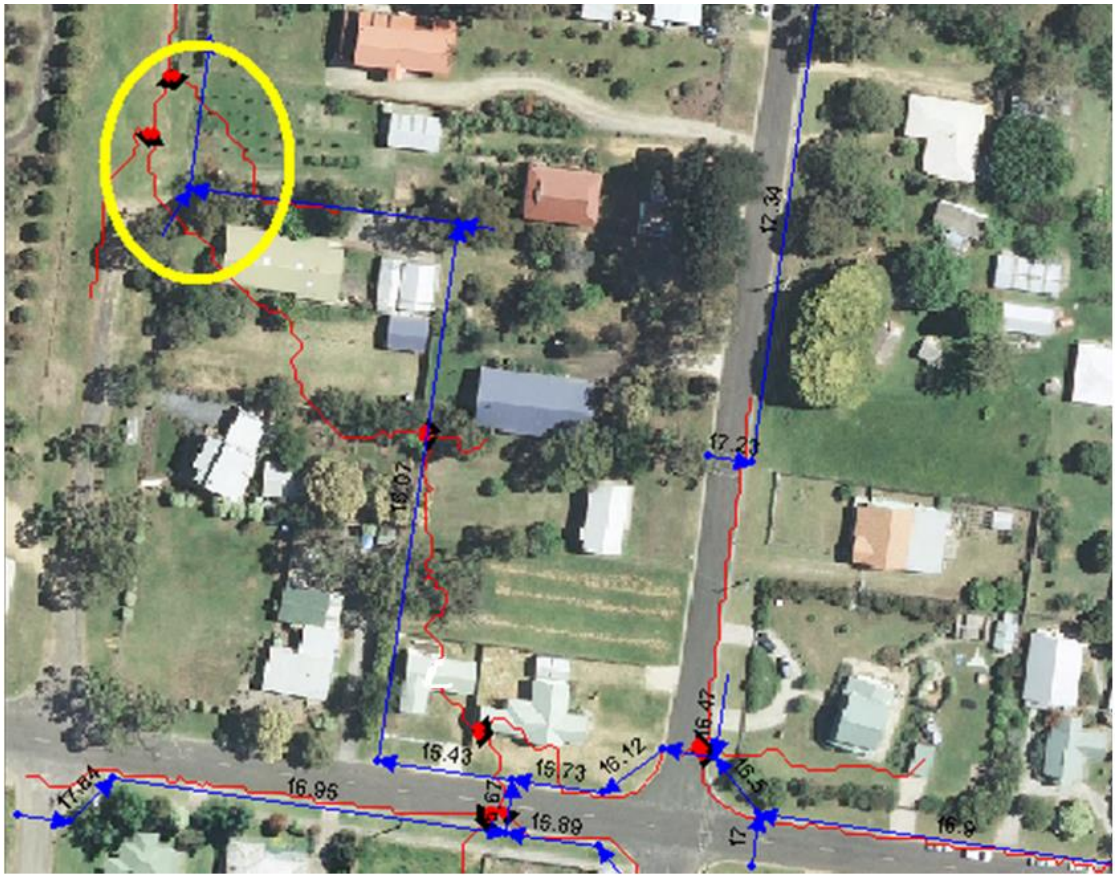


Figure 4-12: Derived flow paths (red), pipes (blue) and the gap between water flow through underground pipes (yellow).

4.5.1 **Legal Point Discharge of the Property**

Scenario modelling for use by urban planners and drainage engineers would be possible using extracted hydrology features (see Figure 4-13).

Figure 4-13: Property legal point of discharge

Such modelling can help drainage engineers to plan stormwater pipe networks for new residential developments. This is of importance with increasing rates of urbanization and the fact that new residential developments aim to have the least impact on the hydrology of the landscape. Based on scenario modelling, it will be possible for the drainage engineers and urban planners to come up with the best management practice.

A ***B***

Figure 4-14: Map B shows the legal point of discharge created by engineers and Map A shows points of discharge created from DEM based hydrological modelling.

4.5.2 Pervious and Impervious Runoff in Coastal Catchments

The benefits of this project on a wider scale include better floodplain management through a better understanding of the increased urban flows that come with increased impervious areas due to urban development, better environmental outcomes through better WSUD applications and a better understanding of SLR due to environmental change and identification of appropriate locations. Figure 4-15 illustrates the modelling of pervious and impervious surfaces that is possible.

Figure 4-15: Modelling of pervious and impervious surfaces. The red areas are impervious surfaces and green areas are pervious

4.6 Analysis of the TWI Model for Coastal Flooding

Water flow is affected by climate change, and when combined with increased urbanization, the result is an increase in the number of people affected and property damage due to flooding. Consequently, there is a need to anticipate changes in precipitation and to adequately configure stormwater frameworks to shield urban residents from flood risk. The research by Pourali 2014, involves developing a LiDAR dataset utilizing SAGA for anticipating future precipitation and analyses at the impacts of climate change on urban overflow in Veronica Street, Inverloch. Changes in precipitation records are first broken down utilizing pattern

examination to extrapolate future two-meter storm flood levels and climate change scenarios. Pourali (2014) used the TWI model based on the Future Coast LiDAR data of the study area. The model can be effectively used to reveal the flooding susceptibility by mapping the flood-prone areas. The procedure to calculate the TWI and the SAGA WI in order to define the susceptibility to flooding (the flood-prone areas) is very straight forward since the selected open-source software Quantum GIS (QGIS) incorporates the respective routines built into the SAGA GIS.

The iterative TWI involves a continuous raster model. The question is, how can such a continuous model be used to generate a classified map of flash-flood-prone and non-flood-prone areas? Manfreda et al. (2011) suggested an equation to determine the value of the threshold to identify flood-prone areas. In spite of the fact that this methodology can precisely decide the degree of the flood, it must be tested and modified for the new test locations (Refice et al., 2013). Moreover, discretionary limits produce diverse outcomes in flood-prone areas. The technique used by Manfreda et al. (2011) requires records of estimation stations, which are not accessible for regions incorporated within the example site, and self-assertive limits make different outcomes. As mentioned, a spatial measurement was utilized in this examination, as described by Anselin (1995) to arrange the TWI model for inundation and non-flash-flood-prone areas.

Using an iterative TWI method, the TWI model was successfully established and that converts a raster TWI dataset to point features. Every point feature is a raster cell in the TWI model. Using the cluster and outlier analysis Pourali et al. (2014a) found that “each point was analysed and assigned to an HH, HL, LH, or LL class. The class with the HH label shows that the point is in a real depression or an overland flash flood-prone area; the other classes were not important in this instance. In addition, the model assigns confidence levels to each point. Using this approach, the TWI model was classified into the flood-prone area (the area formed by points with an HH label)”.

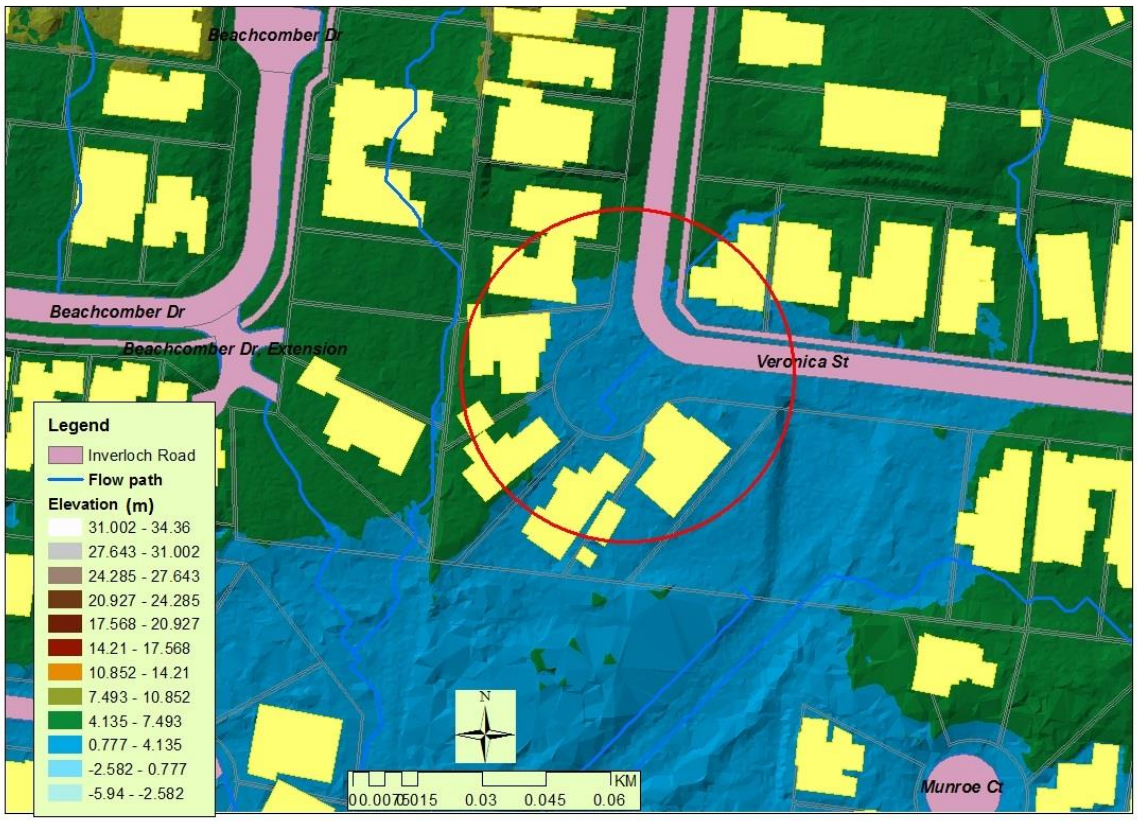


Figure 4-16: DEM of Veronica St, Inverloch, the red circle shows that when Wreck Creek reaches a level of 2m these buildings and streets will be flooded.

A series of flash-floods in 2012 in Veronica Street in Inverloch township has received numerous complaints from residents. The flood in this area resulted from a failure of a minor drainage system to collect storm runoff and some changes in the upstream catchment, notably an increase in the capacity of minor drainage system inlets without any substantial flash-flood modelling. Although the flood event did not occupy a large area, the storm-water stream flowed to the property located in the downslope. Residents claim that the area was not flooded before the relatively large pit inlet-pipe was installed in upstream (as labelled in Figure 4-16).

As mentioned, the flooding in this area related to the failure of the drainage infrastructure. To avoid the flood of residential property, council drainage engineers designed flood water deviations along the path of the natural overland flow down Veronica Street.

The solution was designed at the site-specific level while water movement analysis at catchment scale is also important. Figure 4-16 covers a related area as see Figure 4-17 but this area clearly shows the flood area associated with the topography of the terrain. Therefore, changes in flow, such as installing new inlets or changing land use, will directly affect potential flooding. Increased flow due to flash flooding in the lower stream is greater than the capacity of the inlet pipe.

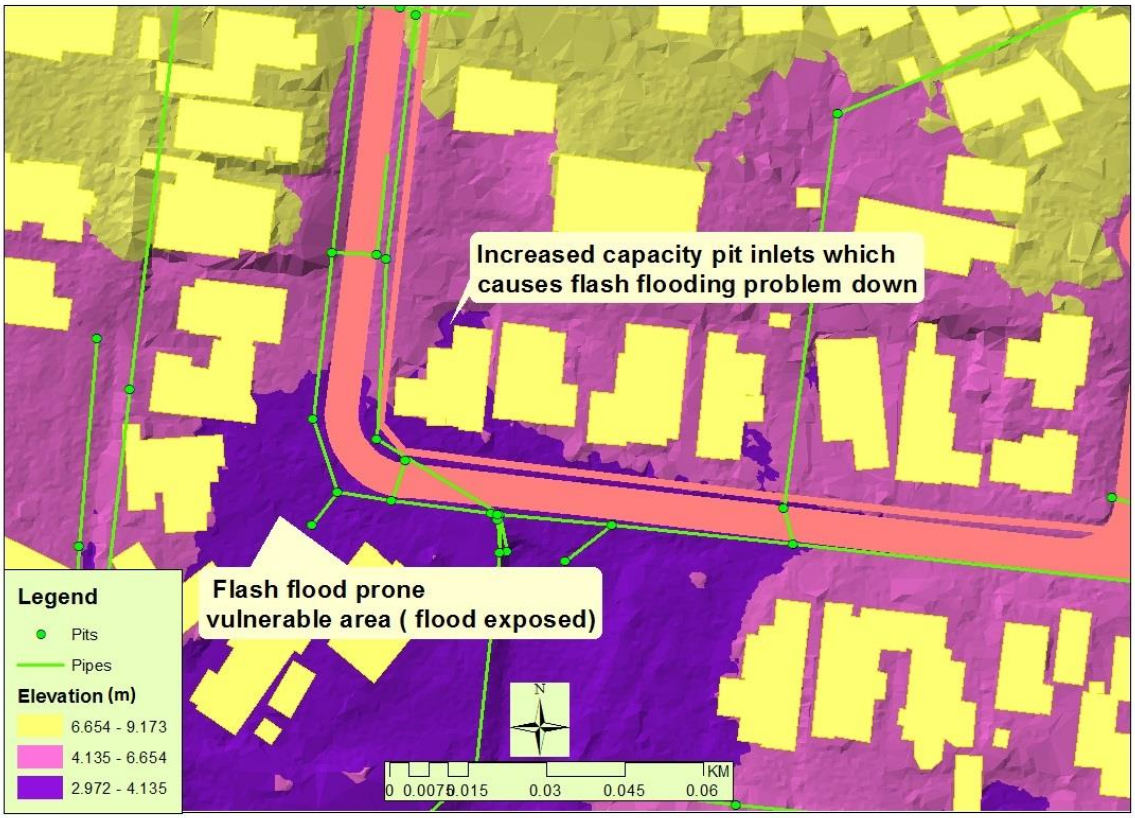


Figure 4-17: LiDAR model shows the flood-prone area in Veronica Street, Inverloch.

Figure 4-17 demonstrates that the LiDAR display was able to provide a map of the flash-flood-prone area in this developed zone. The model illustrated in Figure 4-17 also matches local information collected from the residents who were influenced by the flash flood. They noticed that, in the wake of constructing the upslope pit, flooding had become worse. The impact of climate change viewed through this perspective reveals the local impact, which may be different from the overall impact if the town was simply assessed in isolation. One of the

biggest challenges' communities face is the growing demand for information on residential real estate, including the drainage risk in coastal areas. South Gippsland Water identified Inverloch in 2007 as a place where real estate prices were being driven up by an influx of people with a wide socio-economic profile. As discussed earlier, with climate change expected to raise the average temperature and increase the number of extremely hot days, more moderate increases in South Gippsland and a milder coastal climate will increase the attraction for people from Melbourne (and inland Victoria). This will increase pressure for sub-division adding to social and ecological pressures on the towns.

The combined pressures of population growth and climate impacts will place pressure on services such as water supply and drainage. Inverloch is currently serviced by the Lance Creek reservoir in the Powlett River catchment. While this 4200 ML storage was able to serve the needs of Inverloch and Wonthaggi, in the 2006–07 drought, South Gippsland Water sold supply from Lance Creek to neighbouring Westernport Water where storages had fallen to just 6 per cent of the design capacity. This put extra stress on Lance Creek and raised operating costs (South Gippsland Water, 2007). Future climate change scenarios predict lower flows for rivers in Gippsland of between 5 and 50% by 2070 (DSE, Victoria). South Gippsland Water is now planning to permanently link Lance Creek to Leongatha and Korumburra and Melbourne (South Gippsland Water, 2012). This will increase water security to the same level as Melbourne and lock the community to high Melbourne prices due to the costs of desalinated water (and environmental impacts of the desalination plant).

4.7 Discussion and Results

The BCSC planning and drainage sections can check the overland flow path resulting from proposed subdivisions in the development approval process. It is possible to check every property or unit being developed with connecting channels using overland stream flow and LiDAR hotspot analysis. For the new drainage, the existing pipe system in the area is checked to see if it is large enough to cope with the outflow. If not, a special provision must be made at the development site to temporarily store the stormwater, so the current pipe infrastructure will not be overloaded and will not cause flooding during heavy rain. If the entire pipe system drains correctly and roadways in subdivisions are properly constructed, the council can run a

model utilizing discharge mapping and SLR modelling utilizing existing drainage information to identify flooding issues. This will mitigate the risk to human life and property from flooding in the future.This research has substantially improved the processes that coastal areas can use to protect their communities from potential natural disasters such as SLR, storm surges or flooding events.

When flooding occurs, this is usually due to the pipes reaching capacity. However, the drainage system of the council can be modified, and a program of drainage development program has been created in the yearly council funding program. Sewage problems may occur in some of the old residential areas of the municipality because pipe drains have not been installed as part of the original subdivision.

Council also investigates flooding concerns raised by citizens. For the normal range of rainfall, pipes are designed to a specific capacity. When extreme precipitation occurs, stormwater may start flowing "overland" because this pipe system is full. This can cause problems for residents, especially those who have property in the valleys. When flooding occurs, it is for the most part because the precipitation has been unusually heavy, rather than that the pipes are too small.

With the Department of Environment, Land, Water and Planning (DELWP) providing access to high-resolution elevation data (height data to 10 cm vertical accuracy) through the Future Coasts program, local governments have been able to take a proactive role in preparing their communities for the adaptation of climate change. However, skills at the local government level are not always enough to run the models needed to gain the value provided by the data.

Previously the Council only had access to 10-metre contour information which was very insufficient data for the identification of overland flow. Overland flow assumes shallow sheet flow over a plane surface with an area equivalent to the sub-catchment area. Although this assumption can yield acceptable results, during heavy storms it may lead to false predictions because in flood vulnerable areas the actual flow pattern is significantly different from the

simplified sheet flow. Water tends to pond and flow along preferential paths not only along streets but also between buildings and through other open spaces, and it interacts with outflows from the pressurised sewer network (Maksimović et al., 2009). At the strategic level, the local government must have access to high-resolution elevation data to identify the intricate changes of the grade that affect overland water flows and enable it to better design roads and drainage.

Developing GIS-embedded hydrological modelling tools that will assist in substantially improving the processes that coastal areas can use to protect their communities from potential natural disasters such as SLR, storm surges or flooding events. LiDAR technology is frequently utilized in real-world process modelling, analysis, simulation and visualization (Oryspayev et al., 2012). Such technology is relied upon due to its ability to support forecasting, planning and decision support stages (Sharifi et al., 2009). However, specific applications often require spatial analysis to be improved to meet business workflow requirements. Thus, it is essential to analyse the business workflow for specific applications in the responsible organization and to develop a locally enabled approach to support the role of the business. In this regard, this study contributes to knowledge and understanding of:

- How the model can help the coastal council floodplain management
- The creation of a GIS database with LiDAR datasets for flood-hazard mapping
- How LiDAR data modelling influenced an urban stormwater collection system in a typical GIS-embedded hydrological model, i.e., SAGA and Arc Hydro Tools to improve the drainage of overland flow pathways in an urbanized water reservoir.
- How to establish GIS hydro network analysis capabilities GIS in order to extract watershed boundaries in the presence of a stormwater harvesting system
- Improved flood plain management through a better understanding of the increased urban flows that come with greater impervious areas in Urban Development
- Improved environmental outcomes through better WSUD applications
- Improved understanding of SLR and coastal flooding due to Climate Change
- Clearer identification of high-risk infrastructure.
- Identification and understanding of Flooding Hot Spots.
- Improved Emergency Management Planning and responses.

4.8 Chapter Summary

Chapter 4 answered the following research questions from section 1.2.2:

1. What is the current integrating GIS with a hydrological modelling and multi-source spatial data system?
2. How to use an integrated hydrological GIS model in the integration data sets to provide missing information products in the existing GIS database?

The precision of the basin delineation and the estimation of the terrestrial flow is important in the integration of hydrological and GIS models of urban basins. Delineating basins and flow were a slow process. This study presents two different GIS-based automatic catchments and flows path delineation methods. In this research, the success of the automated methods was also verified. With manual delineation and verified the success of the automated methods. The point clouds can be examined and grouped to create an accurate DTM (Digital Terrain Model), DSM (Digital Surface Model) useful for a variety of GIS-applications like flood plain modelling, analysing forests, determining the height of power lines, hydrological modelling and 3D models.

The LiDAR data to be useful, for example, to generate terrain models, every point in the point cloud must be classified to categorize the points that hit the terrain. There are various software packages that classify the points automatically, but to obtain an acceptable quality manual, checking is almost unavoidable.

The BCSC GIS team has built up its own work process, first to classify the data automatically, and then check them manually to produce an acceptable quality data set that meets the requirement of the council requirements

In general, the watershed method proved to be the best in displaying urban stormwater catchments and the Thiessen polygon technique accomplished better outcomes in sewer catchments. The cost distance method proved to be the most efficient overland flow delineation tool. With the increasing availability of detailed ground topography in LiDAR

datasets, DEM's can be produced using GIS raster techniques. Features such as streets, structures and waterway banks greatly affect catchment dynamics and overland pathways and must be accounted for in the DEM set-up. Reconditioning the DEM to account for structures, roads and kerbs are required for catchment delineation.

This Chapter also demonstrates the ability to perform hydrology analysis for distributed hydrologic parameters which saves time and may improve accuracy compared to traditional techniques. A distributed flow model is suggested. Prepared overland flow paths such as streets, channels and open spaces, remove excess floodwater from houses. LiDAR-based overland flow modelling, LPD and previous information will help to manage coastal flood risk in BCSC.

Successful GIS-based automatic catchment delineation is dependent on the following factors: the degree and availability of data sources, the accuracy of the GIS base data, and the type of system being modelled. Manual "cleaning" of the automated techniques must be anticipated to obtain usable results. The level of cleaning is directly related to care taken with input parameters and the required accuracy for the project. The automated techniques discussed, if used correctly, can significantly expedite the model building process.

Chapter 5 describes watershed delineation of flood risk zones using ArcSwat and addresses objectives and research questions 1 and 2. This Chapter develops models of the area around the catchment or watershed using Victorian coastal LiDAR and other input data from the GIS. This also uses the real-time simulation in ArcSWAT—ArcGIS 10.x and variables obtained from the soil and water evaluation process. In ArcSWAT, for example, the land use, soil and incline are the parameters estimated to initiate the flood. The Chapter additionally discusses the 3D simulation which seems to deliver a visual model for decision-making organizing, the management, and mitigation.

Chapter 5

5 Delineation of Watersheds and Flood Risk Zones using ArcSwat

5.1 Introduction

Whether it is related to stormwater, sewers, or coastal urban watershed flood modelling must include the delineation of catchments and overland flow paths. Of the recent advances in landscape information gathering strategies, the most important is the use of Light Detection and Ranging (Rata et al., 2014). In a review of the application of GIS technology for decision support systems for water management, Rata et al. (2014) argued that combined with improvements in computing power, the data derived from LiDAR and GIS has improved the ability to estimate flood impacts on coastal hydrologic systems.

In this Chapter, the focus is on analysis using the Soil & Water Assessment Tool (Grover, 1999). This Chapter explores how hydrological response units (HRUs) in SWAT can be used to define spatial heterogeneity in land cover and soil types within a watershed. Attribute information was also used with integrated GIS analysis techniques to define exposure to flood risk using hydrological models. According to Cao (2006), SWAT is increasingly being utilized in watershed hydrological modelling as it is considered suitable for assessment for visualisation.

Hydrological processes are dictated by the size and shape of the catchment, as well as its soils, land use, vegetation structure, topography and climate. Spatial and temporal changes in these variables also affect hydrologic cycles within catchments. The identification, specification and simulation of hydrologic processes is critical for understanding how watershed quality, stream physiochemical attributes, and wetland ecology can be impacted by environmental changes. Modern scientific models and geospatial tools are utilised to consider the variability of hydrological processes and how they impact on their surrounding environment (Singh and Woolhiser, 2002).

SWAT has enabled spatial specification and examination of hydrologic processes at various watershed scales (Weber et al., 2009). The model was created by the USDA Agricultural Research Service (USDA-ARS) to estimate the effects of land use on the management of water, sediment, and accumulation of farming chemicals in complex watersheds over time (Sophocleous and Perkins, 2000). As a physically-based model, SWAT can evaluate how surface runoff, groundwater flows, evapotranspiration and soil dampness change within each HRU component of the hydrologic process.

In this Chapter, the topic of terrain processing using GIS-based tools for spatial analysis and ArcSWAT will be explored. ArcSWAT is an ArcGIS-ArcView augmented graphical user interface for SWAT. GIS embedded instruments provide the analytical tools to recognise how water quality and the impact of floods can be relieved by postponing stormwater outfall volumes. During spatial analysis, it is essential to recognize land that is prone to flood events as a result of SLR. The inhabitants of those areas must be aware of the risks of inundation. These issues are discussed to address intermediate research questions one and three listed in section 1.2.2:

1. What is the current status in the integration of GIS with hydrological modelling and multi-source spatial data systems?
3. How can an integrated hydrological and GIS model be used to improve the existing GIS database?

At the end of the Chapter, a brief background of the study area is provided, and the research methods and findings are described.

5.2 Analysis of Hydrological Models

Hydrological models facilitate the analysis of the interrelationships between climate and water resources and can be used to accurately forecast water movement at different stages in the hydrological cycle (Leavesley, 1994). The movement of water is predicted within hydrological models using the water balance equation:

(1)

Where Q is a runoff, P is precipitation, ET is evapotranspiration, and ΔS is the change of water quantity in system storage.

Subject to the complexity of the hydrological processes that occur in a watershed, hydrological models were categorized by Singh et al. (2018) in three ways; conceptual model (grey box), physically-based model (mechanistic/white box) and empirical model (black box). Conceptual models comprise theoretical features that attempt to mimic a real-world hydrologic process. Physically-based models apply the laws of physics to simulate hydrological processes. Empirical models use observed data derived from real-world events to predict hydrological processes being observed (Pechlivanidis et al., 2011).

SWAT, a physically-based model, is increasingly used globally to predict the effects of land use on the management of water, agricultural and horticultural practices, sediment deposition, and indiscriminate contamination in the complex model (Schuol and Abbaspour, 2007). Moreover, SWAT can calculate the long term effects of environmental change on hydrological and biochemical cycles (Ficklin et al., 2009) and has become one of the more prominent hydrological modelling tools utilized around the world. After comparing the commonly used models for hydrological processes (ArcHyro and SAGA and ArcSwat), it was determined that applying the ArcSWAT model would be the most effective means of achieving the objectives outlined in this research.

The content in this Chapter focuses on the application of SWAT model supporting flood prevention in Inverloch. The BCSC is undertaking urgent works to prevent flooding and clear blockages in the Ayr Creek drainage reserve in Inverloch (See Figure 5-1). According to the Council's General Manager of Infrastructure, Ms Felicity Sist, the proposed works include general channel maintenance and flow improvements, urgent waterway maintenance to protect properties in Diane Place from flooding and construction of a permanent levee bank on Diane Place *(Sist, personal communication 2015*). "These works will protect private and Council assets from flooding," Ms Sist said, "*We also have permits from the WGCMA to allow some vegetation clearance in the waterway to allow free flow of drainage water, however, any vegetation removal will be kept to a minimum*" *(Sist, personal communication 2015*).

Figure 5-1: Google map view of the Ayr Creek drainage reserve.

5.3 Analysis of SWAT Hydrological Models

SWAT models have been used globally to solve watershed problems (Zhang et al., 2008). Some recent examples include Githui et al. (2009) in Kenya, Schilling et al. (2008) in Iowa, Jeong et al. (2016) in Korea, Fu et al. (2014) in Canada, Al-Mukhtar et al. (2014) in Germany, Bannwarth et al. (2014) in Thailand and Gassman et al. (2014) in Singapore.

At present, the Victorian Government is considering whether SWAT can be used to predict how land use change will impact on water quality in the Yarra River catchment (Das et al., 2013). Research by Das et al (2013) compared empirical data gathered from the sector of the Yarra River catchment, affected by agricultural practices for the period 1990–2008, with SWAT model outputs.

This research examines the quality of the climate data that is input into the climate dataset in the SWAT model during its design phase and how much manipulation is required to calibrate it to meet SWAT prerequisites in order to generate accurate outputs. The results provide

valuable information for model engineers who are considering applying physically-based models to hydrological modelling in Australian situations. Ashraf Vaghefi et al. (2014) utilized the model to investigate the effect of environmental change on water assets, dry seasons and wheat yield in semiarid districts, Karkheh River basin in Iran.

5.3.1 Hydrological Components of SWAT

The SWAT framework can be activated inside a GIS (ArcGIS) interface, where various spatial information, such as soil texture, climate, ecological composition, land use and topographic qualities can be overlaid. In the SWAT model, the hydrologic processes within the watershed are confined into sub-basins based on calculated DEM (Figure 5-2).

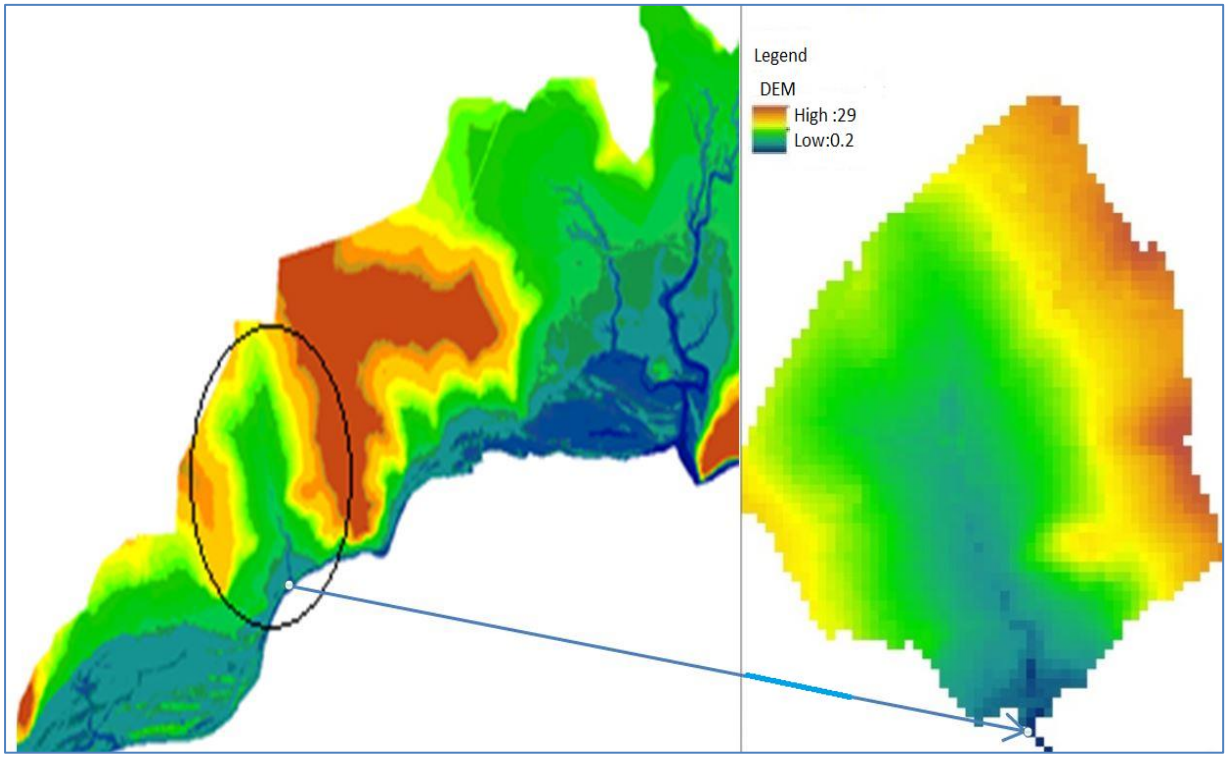


Figure 5-2: Sub-basins in the Greater Inverloch basin and Ayr Creek.

These sub-basins are further disaggregated into Hydrologic Response Units (HRUs). HRUs are defined as areas of land that has uniquely different features identified by slope and soil (Jacobson, 2011). HRUs enables the modeller to distinguish how different soils and land uses

change specific hydrologic conditions (e.g. evapotranspiration). A brief description of the SWAT hydrologic components is provided below in Figure 5-3.

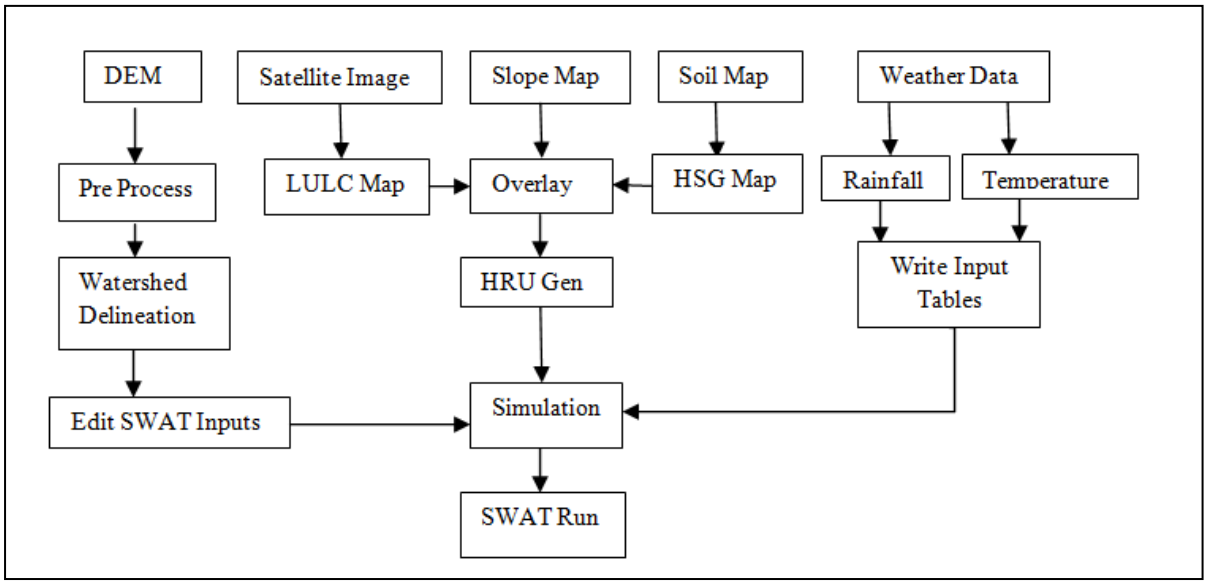


Figure 5-3: Methodology for rainfall-runoff modelling.

(Modified from the SWAT theoretical documentation developed by Neitsch et al. (2011).

5.3.2 **Representation of the Hydrological processes**

The calculation of hydrologic processes is completed in five stages: (1) Precipitation capture, (2) Surface overflow, (3) Soil and root zone penetration, (4) Evapotranspiration and (5) Groundwater flow. In SWAT, the hydrology of a watershed is simulated by first distinguishing two important stages of water movement:

- The Land stage - related to capturing and processing by primary agents (i.e. precipitation captured and processed locally by land and/or vegetation)
- The Routing stage - related to secondary capture and processing agents (i.e. that which is not able to be processed by primary agents and is released into the channel network as runoff).

Hydrological components including surface runoff, lateral flow, groundwater, lake and tributary evaporation and return stream flows are used to define the land stage of the hydrological cycle (Arnold et al., 1998). In the land stage of the hydrological cycle, the simulation of the hydrological cycle is predicted using the following equation:

$$SW_t = SW_0 + \sum_{i=1}^{n} \left(R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw} \right) \qquad (2)$$

where SW_t is the final soil water content on day i, SW_o is the initial soil water content on day i, t is the time in days, R_{day} is the amount of precipitation on day i, Q_{surf} is the amount of surface runoff on day i, E_a is the amount of evapotranspiration on day i, W_{seep} is the amount of water entering the vadose zone from the soil profile on day i, and Q_{gw} is the amount of return flow on day *i(Neitsch et al., 2011)*.

For the model to accurately simulate the evapotranspiration of different crops and soils on the land, larger basins need to be subdivided using the sub-basin loop command into HRUs (Figure 5-4). More in-depth descriptions of how basins can be subdivided to achieve accurate simulation of water movement during the land stage of the hydrological cycle can be found in (Ficklin et al., 2009).

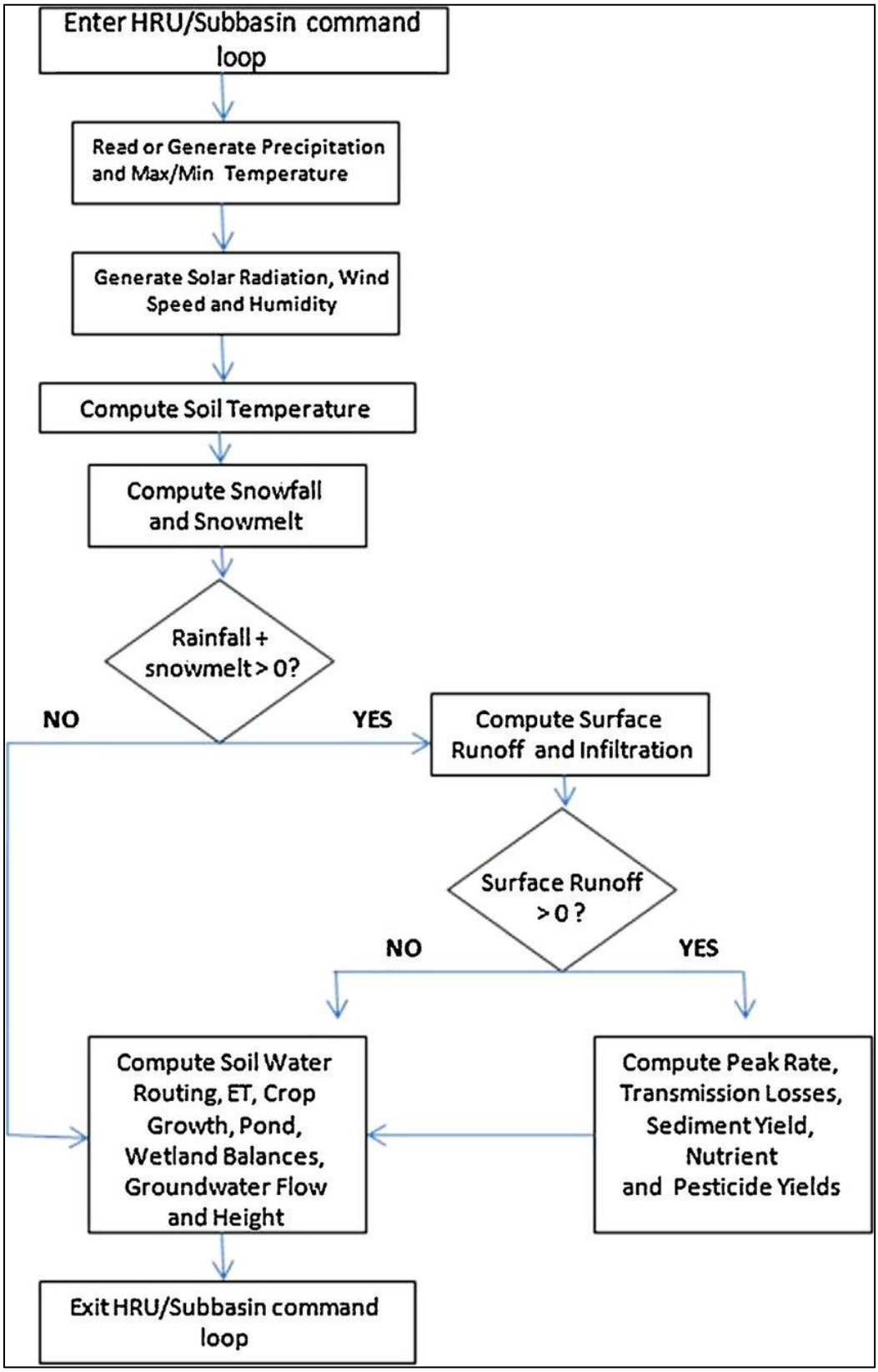


Figure 5-4: The HRU/ Sub-basin loop command (Neitsch et al., 2011)

The stage where runoff water moves through the channel network during the hydrological cycle is the routing stage which is defined as the movement of water, sediments, nutrients and organic chemicals through the channel network of the watershed to the outlet (Arnold et al., 1998). Runoff is modelled separately for each HRU.

The output generated by running the HRU and SWT models is then merged to derive the complete overflow for the basin. Thus, the algorithm used within the simulation mimics real-world water balances more accurately.

The subdivision of basins into HRUs is to allow the model to imitate the adjustments in evapotranspiration for different yields and soils. Runoff is assessed and calculated independently for each HRU and after that directed to pick up the absolute overflow for the basins. This improves the precision of the physical state of water balance.

5.3.3 SWAT Model Input

The different inputs and processes involved in the phase of a hydrological cycle are:

Weather

Daily precipitation and 0.5 hourly precipitations, the maximum and minimum precipitation, air temperature, relative moistness, sun-powered radiation and wind speed are required to run SWAT. SWAT allows its administrators to include climate information from recorded observations or produced in real-time. Australian climate information was obtained from the Australian Bureau of Meteorology (Wasko and Sharma, 2015).

Digital Elevation Model

As discussed in Chapter 2, DEM characterizes "the geography which portrays the height of any point in a given region at a particular spatial goal" (Costabile et al., 2015). In relation to the BCSC GIS database, related metadata archives and reports allowed assessment of the current flood and the management of important spatial datasets and related metadata. The DEM was utilized to get an effective depiction of the watershed and for drainage designs. DEM was acquired from remote sensing satellites or other globally available data sets (Goteti et al., 2008).

Soil Data

SWAT requires information on soil properties such as soil surface, pressure-driven conductivity, accessible water content, mass thickness and natural carbon content for various layers of each soil to run the model. This soil information for the Ayr Creek Basin was obtained from ASRIS Australian Soil Resource (Baby et al., 2018a). The Australian soil map was obtained from an online source - the Digital Atlas of Australian Soils 2010–11: https://data.gov.au.

Land Use

The land use map of Ayr Creek Basin 2002 was collected from the Australian Government/ Department of Agriculture and Water Resources. Land cover images were also available from land use of Australia 2010–11. (https://data.gov.au). Description of Sequential Uncertainty Fitting 2 (SUFI-2)

To evaluate the performance of the SWAT model, the Sequential Uncertainty Fitting ver.2 (SUFI-2) algorithm embedded in the SWAT-CUP package (Abbaspour et al., 2007) was used. The advantages of SUFI-2 are that it combines optimisation and uncertainty analysis, can handle many parameters through Latin hypercube sampling (LHS) and is easy to apply (Abbaspour et al., 2004). Furthermore, as compared with different techniques using SWAT such as generalized likelihood uncertainty estimation (GLU), parameter solution (parsol), and Markov Chain Monte Carlo (MCMC), the SUFI-2 algorithm was found to obtain good prediction uncertainty ranges using different parameters (Yang et al., 2008). This efficiency is very helpful in executing scale models (Abbas et al., 2017, Abbaspour et al., 2007, Schuol et al., 2008).

The sequential uncertainty fitting algorithm (SUFI-2) installed in the SWAT-CUP bundle (Abbaspour et al., 2007) was utilized to assess the execution of the SWAT display. To start with, the SUFI-2 develops the range for every parameter and after that, the Latin Hypercube strategy is connected to deliver various mixes among the alignment parameters. Lastly, the model continues, and the outcomes are calibrated with available information until the best result is achieved. SUFI-2 algorithm the determination coefficient (R^2) and the Nasch-Sutcliff

efficiency (ENC) (Kenchington and Crawford, 1993); (Nash and Sutcliffe, 1970) to assess the closeness of the match. R^2 shows the solid connection between the modelled and recorded information and ranges from zero to one (Legates and McCabe, 1999). The more prominent estimations of R^2 imply less error fluctuation, with values greater than 0.5 are acceptable (Moriasi et al., 2007). R^2 is given by

$$R^2 = \left[\frac{\sum_{i=1}^{n}(O_i - \bar{O})(P_i - \bar{P})}{[\sum_{i=1}^{n}(O_i - \bar{O})^2]^{0.5}[\sum_{i=1}^{n}(P_i - \bar{P})^2]^{0.5}}\right]^2 \quad (11)$$

where O_i is the observed stream flow, P_i is the simulated streamflow and $\bar{O}$ is the mean observed streamflow during the evaluation period $\bar{p}$.

Nash-Sutcliffe model efficiency (ENC) was chosen to be used for alignment for two reasons. First, it was embraced by the American Society of Civil Engineers (ASCE, 1993) and second, Legates and McCabe (1999) recommend it due to its straightforward physical interpretation (Raghavan et al. 2014). Also, it has wide applications offering extensive information on reported values (Moriasi et al., 2007). The observed results compared to the computer-generated values fit the 1:1 line. It can range from negative infinity (-∞) to one. The closer the value to one, the better the model performance is. While a value of less than 0.5 indicates insufficient model performance (Moriasi et al., 2007). ENC is calculated as below:

$$ENC = 1 - \left[\frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2}\right] \quad (12)$$

Where O_i is the flow of the recorded stream flow, P_i is the reproduced stream and $\bar{O}$ is the mean observed streamflow during the evaluation period.

SUFI-2 allows users to conduct plotting the Latin hypercube sampling (LHS) produced parameters against the estimations of the target work utilizing various examinations. At that point, a *t*-test which demonstrates parameter qualities is utilized to decide the relative centrality for every parameter" (Al-Mukhtar et al., 2014). The more delicate the parameter, the more important is the t-test estimate (Abbaspour et al., 2007). In this investigation,

examination, R2, ENC, P-factor and R-factor were received to evaluate the SWAT model performance. “P-factor is defined as a percentage of data covered by the 95% prediction uncertainty (PPU) which is measured at 2.5% and 97.5% of the cumulative distribution of an output variable obtained through Latin hypercube sampling (LHS)” (Abbas et al., 2016).

5.3.4 Hydraulic Catchment Analysis Using SWAT

Understanding the ecosystem services that urban catchments and creeks provide allows managers to design rehabilitation programs with different users end-benefits in mind. When functioning effectively Ayr Creek ecosystem services include improving water quality and moderating floods through holding back stormwater flow. It is fundamental to identify areas that will be inundated by water for the safety of individuals. For many years flooding in the Ayr Creek catchment in Inverloch has been causing great problems for the local community and the environment. The approach in this research is to develop models of the catchment using Victorian Coastal LiDAR and other input data from the GIS.

This study utilizes ArcSWAT within the ArcGIS environment for hydrological modelling of a surface basin and studies the impact of climate change (Krysanova and White, 2015). Land use, soil and slope are the parameters estimated to predict the flood. At the point when certain parts of the hydrologic response unit (HRU), land use, soil or slope are changed because of urban development and environmental change the model can distinguish zones of low, moderate and high flood likelihood. The 3D visualisations then can be used to support the Council in making decisions about the likely flood risk.

According to He et al. (2013) a flood can be characterized as an overflow of water beyond the normal limits of the stream’s bank, spilling into neighbouring land that is normally dry land. The overflow may spread over the floodplain and become a risk to society. Floods are one of the major disaster risks facing Victoria. There have been consistent floods in the Ayr Creek watershed, especially during summer (December to February). However, they have more serious in 2011, 2012 and 2013 see Figure 5-3.

A: Sub-basins ***B: HRUs***

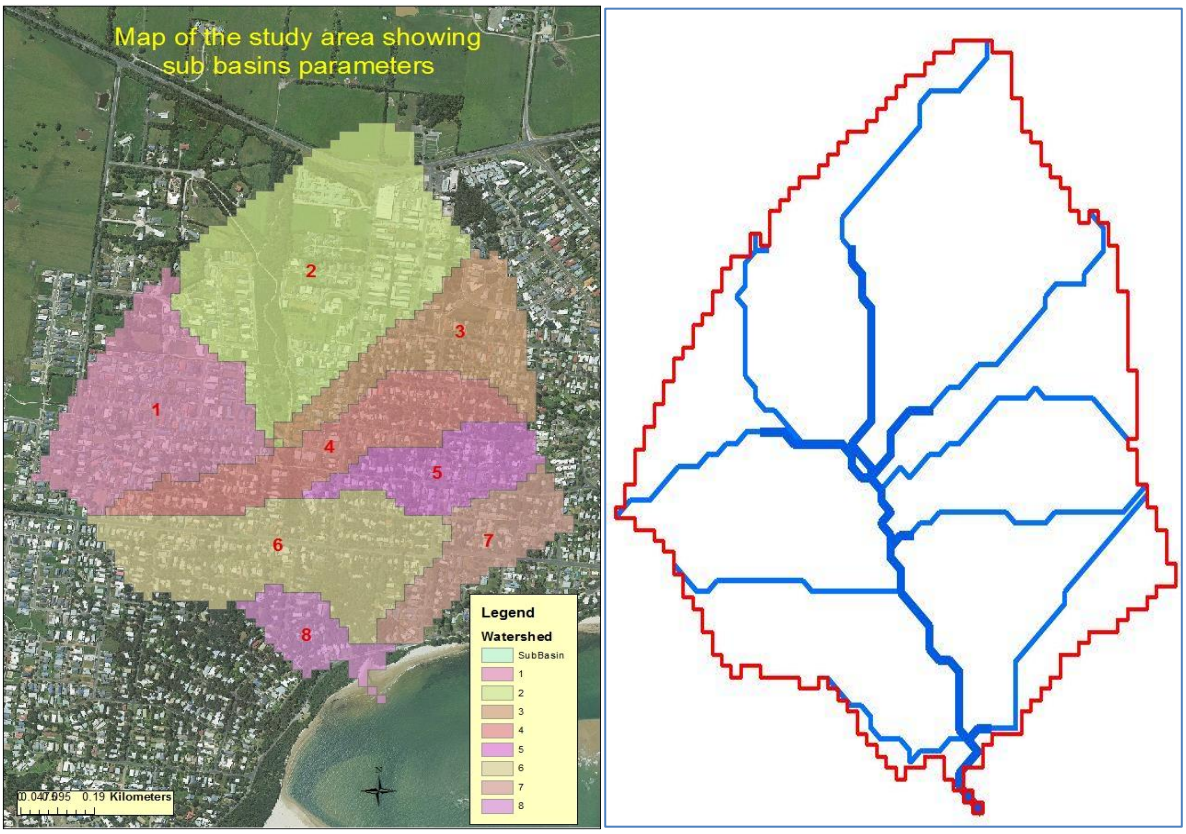


Figure 5-5: A: Study area 8 sub-basins and B:14 HRUs map.

As illustrated in Figure 5-5 above, the SWAT watershed analysis created 8 sub-basins, 14 HRUs and allowed calculation of the total area (see Table 5-1) and the areas of each of these sub-basins (see Table 5-2) below.

Table 5.1: Total area of the watershed

Watershed-Number of Sub-basins	Area [ha]	Area [acres]	Number of HRUs
8	132.50	327.41	14

Table 5.2: Total area of the watershed, building, sub-basin, runoff and Summer Precipitation (mm) 2011' and 'Average Precipitation (mm).

Watershed	Building Area	Subbasin_ Area	runoff2011	sumPRECIPmm2011	avePRECIPmm
1	52634.91	215995.80	111.454	1601.8	133.48
2	49970.39	371605.66	155.372	1601.8	133.48
3	26357.46	128900.71	264.094	1601.8	133.48
4	27634.52	145739.08	215.417	1601.8	133.48
5	17178.77	90578.87	264.017	1601.8	133.48
6	38890.68	225866.59	143.596	1601.8	133.48
7	17296.50	92320.78	240.69	1601.8	133.48
8	7569.51	53998.95	68.807	1601.8	133.48
Grand Total	237532.74	1325006.44	1463.447	12814.4	133.48

Understanding the type of land use is important for flood modelling because different land use affects the amount of runoff and flow. Using the ArcSWAT tools, land use can be characterised for the delineation of a watershed. However, the Victorian land use dataset has a large pixel. size and this affect the resolution of the characterisation as illustrated in Figure 5-6.

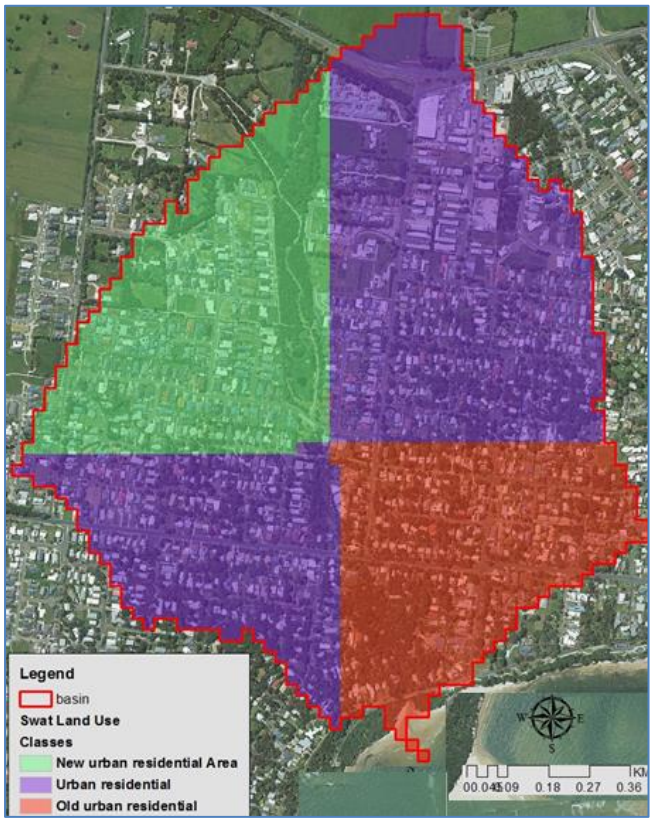


Figure 5-6: SWAT model Land use categories.

The Victoria Department of Environment, Land, Water and Planning (DELWP) is in charge of providing flood gauges and providing guidance to council administrators on when to use them (Alamdar et al., 2017). The utilization of SWAT and 3D has contributed enormously in recognizing regions or zones influenced by flood in each sub-basin inside the Inverloch watershed (See Figure 5-5). The 3D demonstration and re-enactment utilizing the 0.5 m resolution Future Cost LiDAR data DEM were imported into Arc Scene utilizing ArcGIS-3D programming. Previously, individuals created methods for checking flood levels and this empowered them to anticipate the water flow and the hazard or risk included. The 3D representation strategies incorporate photos, for example, satellite images, aerial photos, GIS layers and LiDAR data points. The use of 3D GIS application provides a better platform for flood risk visualization than previously done in2D maps (Chan, 2015).

The 3D data can be visualized and shared with applications such as Google Earth. The KML records are created from ArcMap. Google Earth Pro is more developed than the standard package which enables high picture resolution to be overlaid with other data included GIS

information. It is important to break down the water flow course into 2 metre segments to permit flood checking and transform it from 2D to 3D (Liu et al., 2003). The DEM was utilized to create work in the framework and the waterbody was created for simulation of floods and produce flood models. This can be effectively displayed in a reasonable 3D condition (Liu et al., 2003).

As discussed, flood risk in coastal areas is a key challenge for BCSC. The GIS requires both spatial and non-spatial information. Streamflow is very high during the wet season and therefore the DEM is used to simulate the flow direction at regular intervals to avoid a flood. In the event of a flood, managers need a rapid assessment of the damage, to plan for alleviation activities.

A widespread flood in 2012 resulted from a severe weather event with heavy rainfall across a number of municipalities. Its impact was made worse by the degree of rainfall and flooding experienced a few weeks earlier that had saturated catchments. Emergency services were also challenged by concurrent windstorms. The 2012 report '*Gippsland Flood Event—Review of Flood Warnings and Information Systems*' (Office of the Emergency Services Commissioner, Department of Justice Victoria, 2012, page11) states that:" For a rapidly escalating event in Gippsland, local resourcing provided very limited capacity and minimal contingency for a protracted event". In the later stages of this flood event, personnel from other regions in Victoria were deployed to reinforce key functions in the Incident Control Centre (Pirrone, 2005).

The significant burden imposed by widespread flooding in Gippsland can be managed to some extent by the ability to predict flood risks and consequences across the region, and the potential to focus the dissemination of information about flooding to the wider community. Importantly, directly affected local communities should be targeted. The West Gippsland coastline is vulnerable to coastal inundation during significantly high tides, particularly in conjunction with storm surges. The severity of impacts varies depending on factors including geomorphology, estuary characteristics and the population and infrastructure inundated. In addition, the impact of individual meteorological events on flooding can vary due to precedent

conditions and the dynamics and severity of weather conditions. Assets, including farmland, roads, boardwalks, life-saving towers, foreshores and jetties can be damaged as a result of coastal inundation. Flooding is most hazardous in Inverloch– Ayr Creek (Baby et al., 2018b).

5.4 Results and Discussion

5.4.1 Sensitivity Analysis of Model Parameters

Sensitivity analysis was applied to the 8 parameters related to streams in the SWAT model (Table 5.1), from which the 12 most sensitive parameters were considered for implementing in the model for the Ayr Creek basin. The model parameters used are explained below.

Basin Response Parameters

Three basin response parameters (SURLAG, CH-K2, SFTMP) were used in the SWAT for both the Ayr Creek and the Screw Creek basins. SURLAG (storm stream slack time) characterised the segment in terms of the overall water that enters the reach in one day (Cibin et al., 2010). CH-K2 estimates the flow of water from the channel-bed to the subsurface (Ghaffari et al., 2010). SFTMP is the mean air temperature at which precipitation is liable to become a downpour (Sanadhya et al., 2014).

Surface Response Parameters

As illustrated in Table 5-3, the parameters that control the surface water response used in the SWAT include the overflow bend number (CN2), accessible soil water limit (SOL-AWC), the soil dissipation pay factor (Wescott, 2004), normal slant length (SLSUBBSN) and incline steepness (HRU-SLP). CN2 is used to evaluate the amount of runoff resulting from the precipitation occasion. It is derived from a set of basin properties including land use, soil type and forerunner dampness condition (Arnold et al., 2012). The more prominent the CN2, the more important is the produced surface overflow (Sanadhya et al., 2014). SOL-AWC is a measure of water that is accessible to plants for take-up when the soil is at a field limit. It is evaluated by subtracting the measure of water existing at the changeless wilting point from the current level at a field limit (Arnold et al., 2012). ESCO is the soil evaporation compensation factor (Cibin et al., 2010). SLSUBBSN is estimated at the point in the main channel that the stream begins to concentrate (Arnold et al., 2012). HRU-SLOP is the average slope steepness (m/m).

Table 5.3: Description of SWAT input parameters related to flow (Arnold et al., 1998)

Group	Parameter	Description	Unit
Soil	SOL_Z SOL_AWC	Depth to bottom of the second soil layer Available water capacity	Mm
Groundwater	ALPHA_BF	Baseflow Alpha factor	Days
Groundwater	GW_DELAY	Groundwater delaty	Days
HRU	SLSUBBSN ESCO	Average slope length Plant uptake compensation factor	M
Management	CN2	Initial SCS runoff curve number for moisture condition II	
General data basin	SLOPE	Slope	

Sub-Surface Response Parameters

Table 5.3 show adjustment parameters are used in the sub-surface water response in GWQMN is an immediate record of groundwater-stream reaction to changes in energies (Arnold et al., 2007). GWQMN is the threshold depth of water in the shallow aquifer for return flow to occur (Winchell et al., 2007).

5.4.2 Sensitivity Analysis for Ayr Creek

The ranking of the 5 most sensitive parameters for the Ayr Creek basin is listed in Table 5.3 CN2 was the most sensitive parameter. In most SWAT models in different watersheds, CN2 is seen to be the most sensitive parameter (Cibin et al., 2010). CN2 mostly affects the measure of overflow created from the HRU; along these lines, generally high sensitivity can be normal for the greater part of the basins (Veith et al., 2010). ALPHA-BF was seen to be the second most sensitive parameter and the most delicate parameter among groundwater parameters. This outcome agrees with the findings of Li et al. (2009). They found that ALPHA-BF is a sensitive groundwater parameter in SWAT calibration. GW_DELAY was positioned third. It can be noticed clearly that CN2 and ALPHA_BF are the most sensitive parameters for Ayr Creek basin.

Table 5.4: Ranking the 5 most sensitive parameters related to current flow in Ayr Creek

Parameter	*Rank*	*Initial values*	*Fitted values*
ALPHA_BF	2	0 – 1	0.95
GW_DELAY	3	30 – 450	401
HRU_ SLP	6	0 – 0.2	0.01
SLSUBBSN	10	0 – 0.2	0.13
GWQMN	12	0 – 2	1.83

5.4.3 Calibration and Validation

In the Ayr Creek basin, SWAT was calibrated and validated at one weather station, Pond Creek, which lies at latitude 38.6041°S, and 145.8628°E. At the Pound Creek weather station, the calibration period, R2 and ENC (Nasch-Sutcliff efficiency) were 0.72 and 0.63, respectively. In the validation period, R2 and ENC increased to 0.95 and 0, 89. The values of ENC and the R2 index were higher than 0.50 for both calibration and validation. Based on the R2 and ENC values, the model performance can be judged as satisfactory (Moriasi et al., 2007, Abbas et al., 2017). Generally, the SWAT model was unable to capture high flow events. It is typical of mathematical models to under-capture extreme events if not specifically focused on them. SWAT is not designed to simulate extreme hydrological conditions (Lai et al., 2005, Cheng et al., 2006). These results are consistent with those of Rostamian et al. (2008), , Santhi et al. (2001), Ndomba et al. (2008), Güngör and Göncü (2013), Zhang and Pan (2014a) and Abbas et al. (2017).

HRUs are packages groups of land that have a solo land use area, slope and soil within the boundaries of the sub-basin (Abbas et al., 2016). HRUs Land Use/Soil/Slope thresholds were: 10 / 10 / 10 [%], Number of HRUs: 13, Number of Sub basins: 8. The total area of the watershed is 132.50 hectare or 327.41 acres. The total number of sub-basins was 8 characterized by 13 Hydrologic Response Units (HRUs). The thresholds of 10/10/10 per cent were selected (10% slope threshold combination gives a better estimation of streamflow). The flood risk event has been enabled by developing real-time simulation in a 3D scenario. This

became apparent when the use of GIS was employed to solve the problems of flood risk. This is done through visualization of selected zones affected by floods in Ayr Creek.

5.4.4 Catchment Delineation

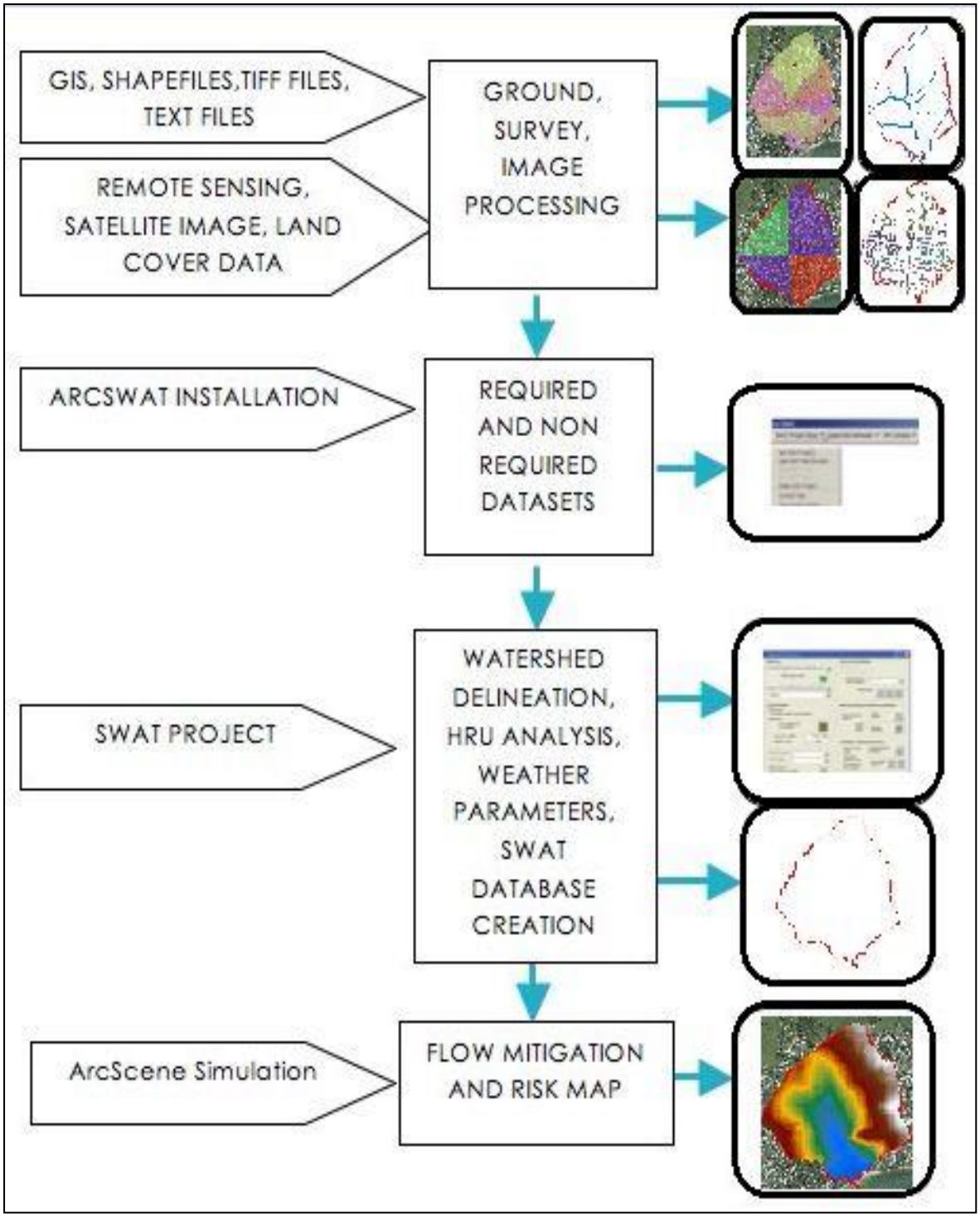


Figure 5-7: Flow Chart for Watershed Delineation using SWAT Model

The results from the SWAT watershed delineation are presented in Figure 5-7.

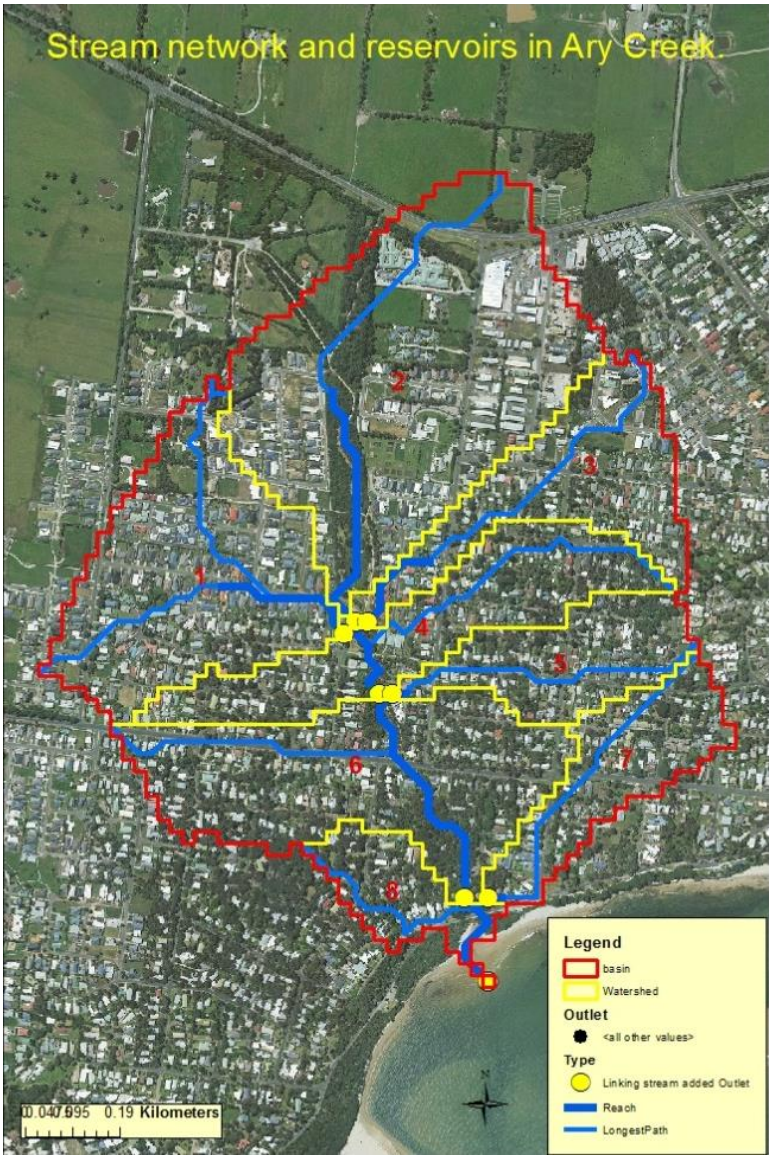


Figure 5-8: Watershed delineation, Stream network and reservoirs in Ayr Creek.

A watershed is often called a basin or catchment, which is a territory depicted with a predetermined outlet point that flows into an extensive waterway. Figure 5-8 shows the portrayed watersheds of Ayr Creek Catchment.

The stream connections and stores are created through the stream arrangement. In total, twelve (12) stream connections are acquired from the Ayr Creek Catchment. Each stream interface

had been associated with a specific sub-basin. There are around eight distinctive sub-basins in the examination zone. Each of the sub-basins was portrayed by a unique parameter for grouping and hydrological analysis. Figure 5-8 demonstrates the ordered sub-basin in the Ayr Creek Catchment. In the hydrologic reaction unit (HRU), an examination from the SWAT, four major sub-basins were discussed. Sub-basins number 5 and 8 were chosen as the smallest sub-basins in the Ayr Creek catchment at 14.45 hectares in the SWAT region of 10.56%.

5.4.5 Slope and Soil Map Analysis

The land cover types found within the sub-basins include Residential-Low Density and transportation. The soils found within the sub-basins are the local soils called LOAMY-SAND. The slope ranges between 4.78% and 95.22%. Figure 5-10 shows the classified slope in the Ayr Creek Catchment.

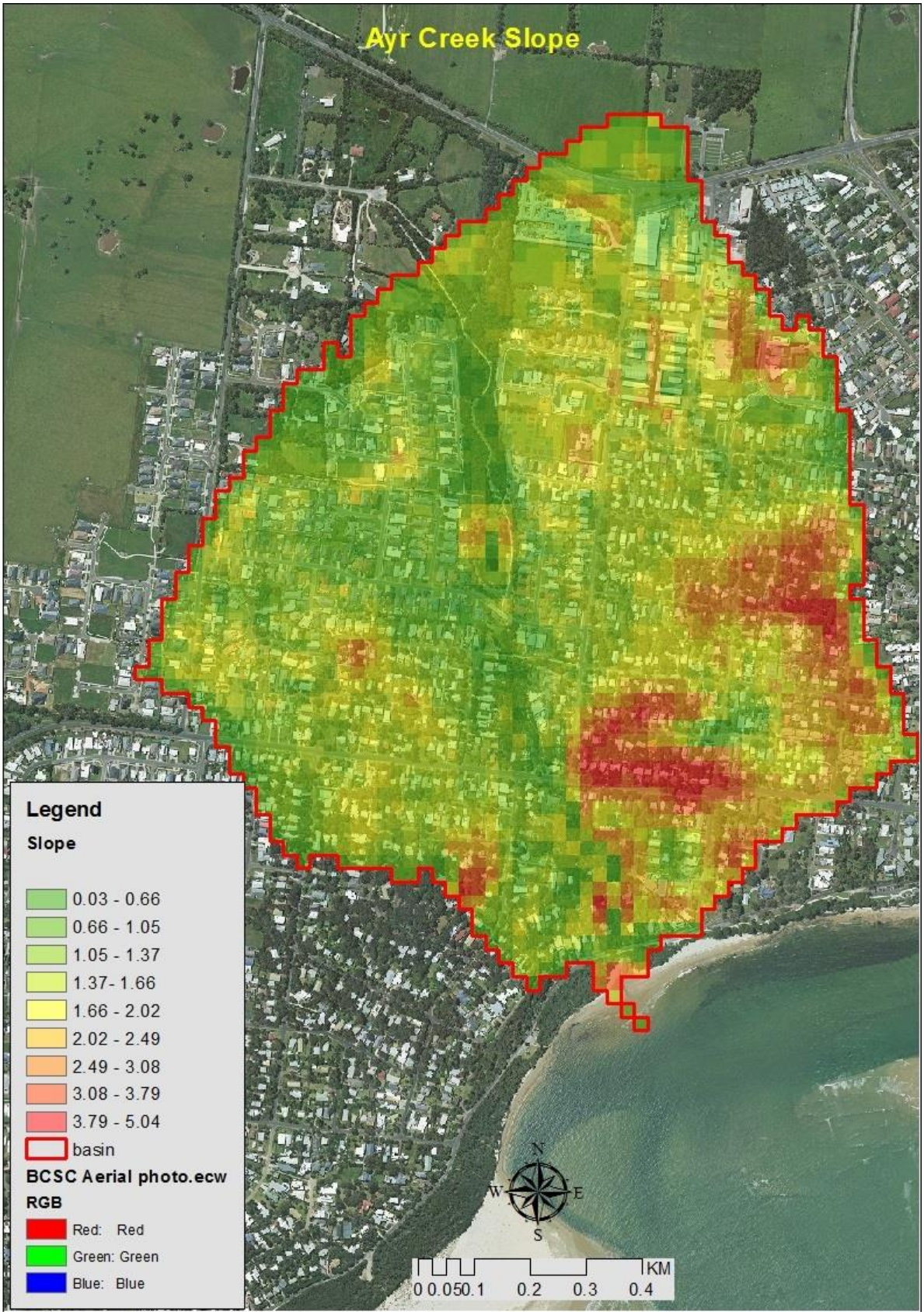


Figure 5-9: Ayr Creek Slope Map

Moreover, number 2 sub-basin is 37.16 hectares with an overall SWAT region of 100% with a land cover of urban built-up area and water. The local soil type is called LOAMY-SAND. Aside from soils in waste disposal areas, the surface soils form very dark grey clay loams to gravelly loams and occasionally loamy sand. This overlies a light grey or light brownish grey comparatively finished subsurface soil at around 20 cm in depth underneath the coastal zone, the subsoils are quite variable.

The largest sub-basins found in the catchment area of the Ayr Creek are the sub-basins number 2 and 6. Number 2 sub-basin is total area 37.16 hectares with a SWAT area of 28.04 %; the land covers include 192 buildings and a total building area of 54,000 sq m (Table 5.5).

Table 5.5: Totals of pervious and impervious surfaces.

Years	**m^2 2012**	**%**
Basin	1325006.43	
Building	237532.74	17.92
Road	113088.64	8.53
Total Impervious area (buildings, roads)	350621.38	26.45
Total Pervious area	623763.67	73.55

The individual example of the land coverage incorporates timberland, water, urban land use, and the fields are explained below. The soil characterization depends on the USGS with the default SWAT soil database. The local soil data is uploaded into the SWAT model based on the CSIRO soil map. Table 5.6 demonstrates the outcome of the classification with the total areas in hectares, square metres and the total per cent area obtained during the analysis (table 5.6).

Table 5.6: Slope result

ID	**Area (m^2)**	**Area (ha)**	**%wat.Area**
0	268404.64	26.84	20.39
1	800183.64	80.2	61.23
2	189022.49	18.2	13.83
3	50650.26	5.07	3.58
4	11592.61	1.16	0.88
5	1161.27	0.12	0.09

Soils can lose moisture and become cooler or warmer quickly. Depending on the temperature, the water retention capacity varies from a wet climate to a semi-arid environment. SWAT model is limited used in Australia, mainly because of data-poor environment. Land is the Ayr Creek catchment is steep with an average slope percentage of 61.23%, and it is most likely to have a poor water retention capacity. The slope data derived from the SWAT database was created for Slope in the Land Use, Soils, Slope definition using the automatically generated single slope classes of 10/10/10 per cent from the HRU. Table 5.6 shows the result of the total area from each category of slope in hectares while also showing the slope per cent from 0–10 up to 40 meters above. The slope map of the Ayr Creek catchment, shown in dark red (see Figure 5-10), depicts the lowest elevation, i.e. 0–10 meters. The green pattern is a 10–20-meter slope, the blue is between 20–30 m and lastly, the light grey in the map represents the greatest slope.

5.4.6 **Creek Discharge**

The flood risk model was developed as shown in Figure 5-10. This was used to measure the magnitude of the flood risk in the catchment area of Ayr Creek. Here we arrived at the categories of flood risk from the highest risk to moderate and no risk zones within the watershed. The flood risk map represents the risk zones which can be used for mitigation, planning and a warning to the public.

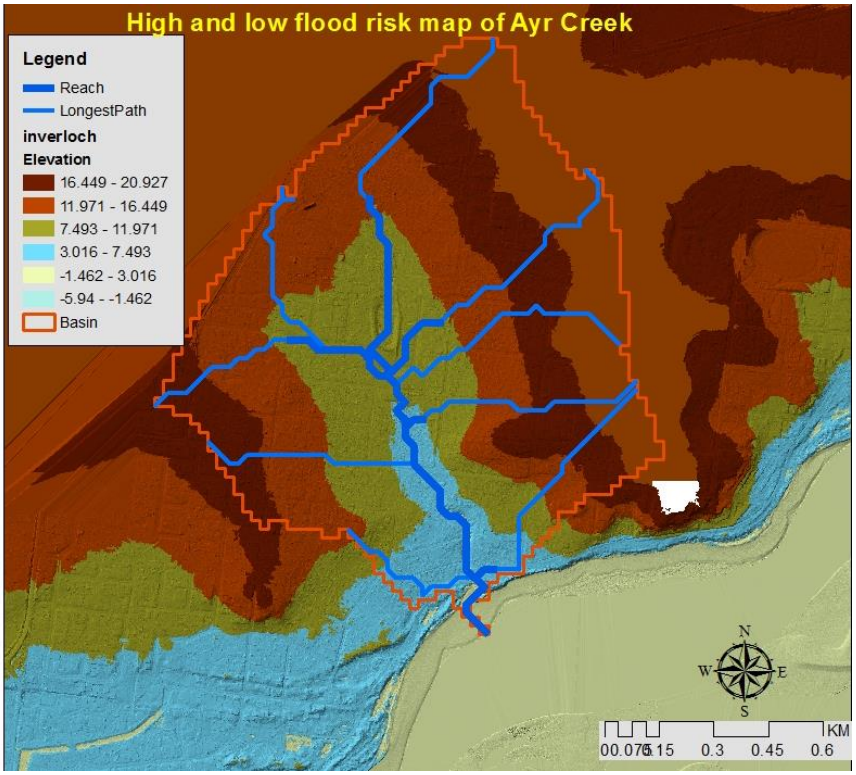


Figure 5-10: Range of flood risk within the Ayr Creek catchment

The clearing of vegetation in Ayr Creek will significantly affect the floodplain zones which are predominantly occupied by the creek. While both zones are at flood risk, the presence or absence of more land cover will ultimately change the water flow. The aftermath of a flood event usually is associated with pollution. Dirty water with refuse and garbage and blocked drains might cause an outbreak of skin disease; or the risk of lives through broken cables that can easily electrocute humans and live animals.

The 3D flood models were produced from the digital elevation model of the study area and were mask of a layer overlaid. The Ayr Creek water level was considered as the base height. Figure 5-10 describes the 3D model developed by ArcScene. At this point, the simulated Z values are used to create the 3D visualisation or animation in ArcScene. The real-time simulation was displayed; the purpose is to create a quick alert or warning through animated video. Perhaps all the areas prone to flooding will be easily identified and mitigation action can be applied.

5.4.7 Comparison of Arc Hydro and SWAT

ArcGIS extension ArcSWAT and Arc Hydro are used for watershed modelling. High resolution LiDAR-based DEM is used to delineate the accurate watershed. The research in Chapters 4 and 5 aims to undertake hydrological modelling using two different modules but with the same data set. These two modules provide different ways of analysing the DEM and watershed delineation. The reason for this analysis was to determine which extension gave a better assessment of a watershed. Information was gathered for the Ayr Creek watersheds and brought into each model. The ArcSWAT module allows different data to be joined, such as climate data, precipitation, land use, and soil type. It is ideal for small watershed studies (Sundaram and Yarrakula, 2017). ArcSWAT automatically makes processes while Arc Hydro provides physical selections of the watershed. ArcSWAT provides more detailed information for hydrological response units (HRU) than Arc Hydro (K et al., 2012).

ArcSWAT can derive an increasingly precise delineation of the watershed, particularly for smaller watersheds like Ayr Creek. Arc Hydro exceeds expectations for Council officials, allowing improved decision-making about when information should be gathered and incorporated into the model, especially for bigger watersheds like Inverloch. This is consistent with the analysis by (Bryan and Curran, 2004) who found that ArcSWAT better represents field data, and provides the analyst with more control over the physical techniques being shown. ArcSWAT is easier to use for researchers with little GIS understanding and experience. However, for researchers with more advanced GIS programming capacities, Arc Hydro is more adaptable. This Chapter also includes a description of 3D analyses by deriving TIN contours, models and arrangements of stream networks over the land surface, using LiDAR as the base layer. This data analysis can support decision making and flood control planning. The two-dimensional visualizations are not enough in presenting the true landscape and so cannot make a full illustration of data available.

A: ArcSWAT ***B: Arc Hydro***

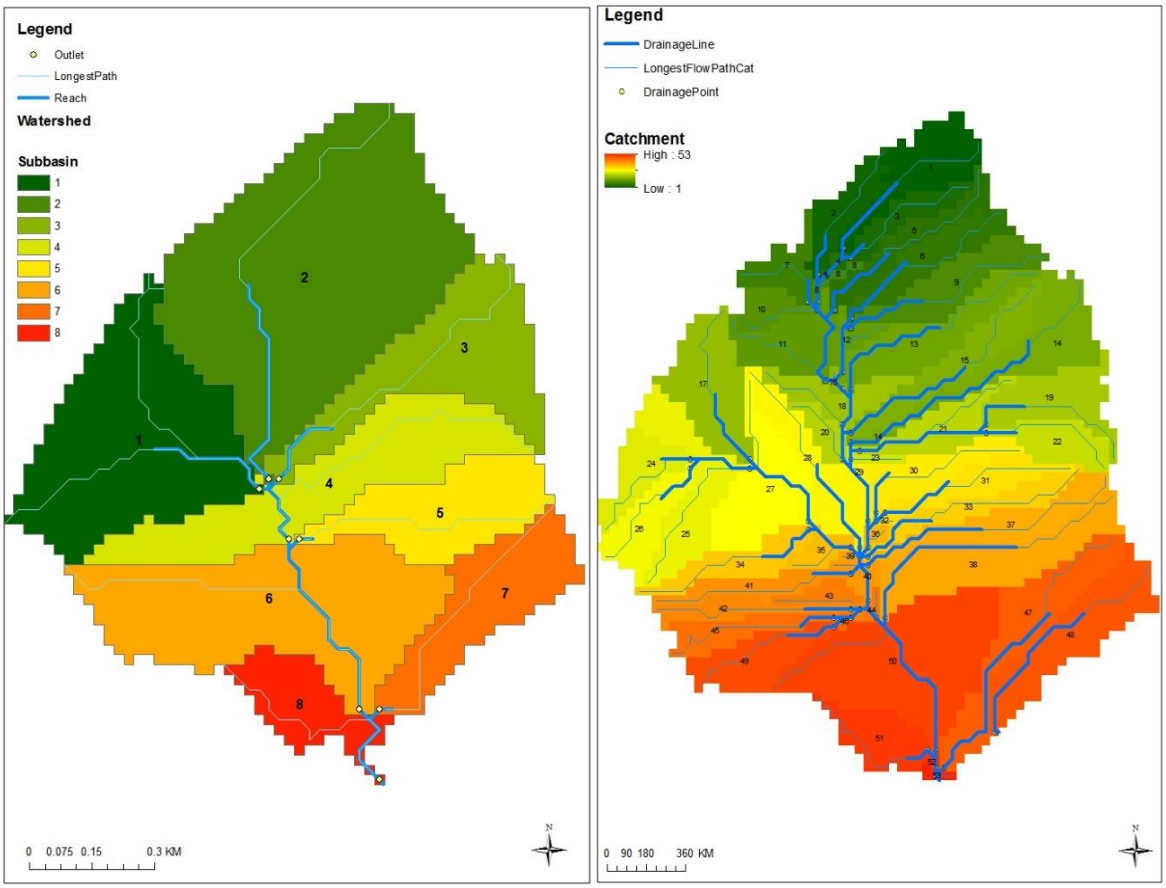


Figure 5-11: a) Ayr Creek sub-basins map using ArcSWAT and b) Study area sub-basins map using Arc Hydro

5.5 Chapter Summary

This Chapter discussed the usefulness of the hydrological models incorporated in GIS and the available DEM derived from high-resolution LiDAR data to provide the information products needed to determine overland flow paths in detail in the coastal basin. The results of the research presented in this Chapter were the new processes of integration of spatial data that allowed the extraction of the overland flow path and the detail of the catchment basin in the coastal area. This Chapter started with a review of the relevant literature. Based on the intermediate research questions 1 and 3, appropriate measures have been developed to extract the hydrology modelling process for the analysis of drainage in the context of climate change.

This research provides enhanced data and information for decision making and flood control management. At present, the two-dimensional (2D) approaches are not adequate and can't

fully portray the watersheds. Today, geographical 3D simulation and modelling are regarded as a fundamental approach to solving complex geographic problems. The best practice approach to simulate real-world events is to use modelling techniques that produce three-dimensional (3D) geographic simulation products.

Topographical 3D modelling is an effective way to address complex geographical issues. ArcSWAT has allowed modelling of the individual sub-basins for the Ayr Creek catchment where around 25 sub-basin parameters (listed in Figure 5-11b) are acquired in the catchment. The watershed that was depicted involves sub-basin parameters where each sub-basin has unique qualities of a hydrological response unit (HRU). The vulnerability pattern in flood assessment in 3D allows for a rapid response, alerts and threat warnings, extenuation, planning, and management. Each time there is a flood in Ayr Creek catchment, geographical 3D simulation and modelling are regarded as a fundamental approach to solving complex geographic problems. This information is useful for urban managers, surveyors, environmentalists, architects and geologists. The issue of flood disaster is a global phenomenon that requires attention to save lives and properties. There is a need to monitor the activities of the flood by applying GIS (Wang and Xie, 2018).

The present flood models were developed to predict the coastal areas that may be flooded during a storm assuming that the coastal landscape is represented by a digital elevation model which will not change during the event. Results in Chapters 4, 5, 6, and 7 show different flood tools developed for coastal areas based on the calculated exposure to coastal erosion of buildings and infrastructure. Very limited research has been undertaken on this and it is the basis of the next Chapter.

Chapter 6 outlined the adequacy of the current process for the analysis into the drainage in the context of climate change. Responding to intermediate research question three (Listed in Section 1.2.2). The next Chapter will focus on:

- The Blue Spot Model and affected buildings and roads
- Scenario-based coastal flood risk analysis related to critical infrastructure.

Chapter 6

6 Finding Areas at Risk of Flooding in a Downpour

6.1 Introduction

Chapter 2 discussed the duties and roles of Australian government organizations, and the importance of coastal land use planning in reducing the damage from riverine, overland flash flooding and sea level rise. In Chapter 3, the pilot study area and the reasons for selecting the location were introduced. The area is the Bass Coast under the jurisdiction of the Bass Coast Shire Council (BCSC). In Chapters 4 and 5 GIS embedded hydrological modelling was discussed.

In this Chapter, the procedure for conducting a pilot study for flood-risk aware or focused coastal land use planning is described, along with the existing GIS database in BCSC to support land development decision-making. For flood-risk aware or focused planning policy to be put into practice, it requires a business workflow, specific information products, and a spatial database. Moreover, to develop a comprehensive flood-risk GIS database, a dataset with an appropriate scale, with enough spatial detail and appropriate attribute information is required. GIS-embedded hydrological models should also be linked to the database. These matters are discussed to provide a framework for answering the intermediate research questions four and five listed in section 1.2.2:

3. How can the current process for drainage analysis be improved?
4. How does a spatial decision support system help to identify infrastructure at risk from SLR induced flooding?

In the rest of this Chapter, a brief background of the study is presented and methods and findings are demonstrated.

6.2 Background Literature on Blue Spot Modelling

In Chapter 6, the duty of local governments for floodplain management and especially for flood risk reduction in Victoria is outlined. Also, the reliance of the local governments on the

flood mapping information created by CMAs, and on Melbourne Water flood data is discussed. The BCSC area faced heavy precipitation in May 2012 and higher than expected precipitation in August 2012. Phillip Island received over 90mm of rain, including 55 mm in one day, nearly achieving the normal September precipitation in less than 24 hours (BCSC, 2013). This heavy downpour caused flooding over the district, including areas that are usually prone to flood.

As discussed earlier in the thesis, precipitation is the main source of major floods in Australia (Geoscience Australia, 2013, Bureau of Meteorology, 2013). Floods caused by rainfall are either river floods or underground floods. Although flood behaviour varies with the topography, the approximate geographical extent and time of flooding can be predicted by utilizing precipitation-runoff models. Stormwater flash flooding happens during storms and causes an overflow as it has surpassed the limit of the subsurface stormwater infrastructure (Walsh et al., 2019). Overland flash flooding also happens when runoff moves over the ground towards the closest topographic discouragement territory, ordinarily in developed or rustic areas secured by impervious surfaces which volume can be increased, not quickened. Although flash flooding occurs over small areas, its damage is frequently more severe than a riverine flood because of very little warning time (Mata, 2017). For instance, in 2005 riverine floods compromised around 20,000 properties in Melbourne, while stormwater flooding in a similar area threatened 82,000 properties (Mata, 2017).

In recent years, Melbourne has experienced several sudden, extreme rainfall events. On 30th Dec 2016, the State Emergency Service (Assessment) received more than 2,500 calls for assistance since the heavy rain hit, with Melbourne's north, north-east and south-east suffering the most flood damage (News, 2016). At the height (peak) of the storm, about one millimeters of rain was falling per minute, causing rivers to burst their banks. Claire Yeo from the Bureau of Meteorology Severe Weather Meteorologist reported that rain fell in a short space of time, with up to 70 millimetres recorded in the Dandenong Ranges in half an hour (News, 2016).

This research project was designed to develop a screening method to assess building and roads in flood prone areas. To do this using Blue Spot Model (BSM) a map of Inverloch was

developed – which identifies low-lying areas that have no natural drainage. A blue spot is an area where there is a relatively high likelihood of flooding and the consequences are significant. In a cloudburst (extreme rainfall event), blue spots may fill up and overflow, damaging buildings and roads that lie within and adjacent to them. BSM tools will support flood-risk sensitive land use planning at the local level and allow the usage of new forms of information to assist in the decision process.

The key aim of the BSM tool is to support local government prepare for future cloudbursts (extreme rainfall events). The following sections present a method for creating a BSM, the development of a screening method to assess buildings and roads in high flood risk areas, and a geoprocessing model. The geoprocessing model involves analysis, data management, editing, and other operations that use elevation data to find the locations of blue spots using a BSM. The study area is in Inverloch, but the models have international applicability because the criteria consist of the land surface, buildings and streets. An underlying hypothesis is that the DEM generates a reliable flow direction surface; this hypothesis has been improved for DEMs with higher resolution (Tiwari et al., 2017).

Drainage flow models will not work in spots where water does not flow out. Low-lying regions— such as depressions, sinks, or hollows are very common and come in all shapes and sizes. Landscapes that look flat may contain shallow depressions that trap rainfall.

Some residential areas are developed in low-lying areas where depressions are not noticed under dry conditions. It becomes evident during a downpour that the ground can't naturally drain, and the stormwater system doesn’t function effectively. Coastal building, streets, infrastructure, tram stations or railroad tracks are also vulnerable (Balstrøm and Crawford, 2018).

Low lying areas, whether cultivated or developed, present some risks. On farmland, there can be a threat to crops and equipment. Construction in built-up areas causes house flooding unless buildings are built on high ground. Infrastructure not in depressions may still be at risk

as during heavy rainwater flows towards the discharge point, and adjacent areas may be flooded.

Morris et al. (2018) developed a DEM to provide overland flow paths and catchment boundaries. GIS and hydrological modelling can help assess the local nature of flood risk and identify areas where new residential housing may be at risk of flooding. Before the residential development, the drainage was efficient as some water was able to drain through pastures into the underground water basins. However, in the BCSC region, several developments have been located on land that was once wetlands or small lakes and was typically agricultural land. Today, some houses exist in low-lying areas where water accumulates during an event of extreme rain. Homeowners living in these low-lying areas that have been converted from agriculture to residential housing face the challenge of frequent flooding.

Figure 6-1: Left: an orthophoto map from 2010. The green areas are low lying grasslands and a creek. Right: the same area in 2018 is now a residential development which used to be a part of the agricultural area (Source: Google Earth).

Spatial data is fundamental to hydrological modelling of real-world hydrological forms (Devia et al., 2015). Despite the complexity of stormwater management in urban catchments (Roy et al., 2008), as discussed in Chapter 4, site-specific and catchment-scale runoffs are assessed using the BCSC existing overland flow path model and catchment boundaries. Thus, existing catchment boundary and overland flow paths datasets provide the basic information for implementing flood-risk informed land use planning. It does this through a GIS-embedded hydrological model, for which each land unit has its hydrological situation (Pourali, 2014). In

the remainder of this Chapter, the methods for developing the BSM based map using the GIS-embedded hydrological model are also described. In describing the overland flow path model, rainfall information is used in a sample site as a pilot study. The following section concludes with the investigation results.

The BSM Fill Up Values is underpinned by a workflow for classifying landscape sinks and making a quantitative assessment of flood risks to buildings in the event of heavy rainfall. For example, two Danish companies, NIRAS an international consulting group in Europe) and COWI an international consulting group, specialising in engineering, environmental science and economics, based in Lyngby, Denmark) have developed BSM based maps for Denmark (Howari et al., 2007).

This Chapter presents a comprehensive GIS-based decision support tool that integrates with BSM for effective management of coastal flooding. The BSM is customized and used in the pilot study area. This model is updated based on the current overland flow, the catchment and highlights blue spot areas - low lying areas and sinks where flooding risks are higher (See Figure 6-2).

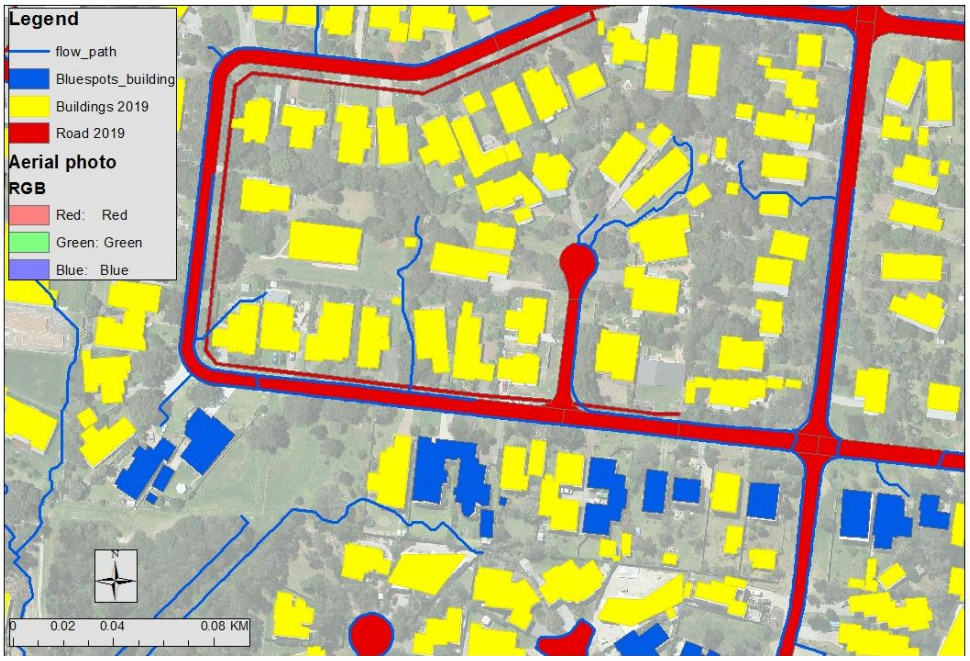


Figure 6-2: The BSM based map of the lowland area identified with the Future Coast LiDAR data 2009.

Figure 6-2 shows the results of the assessment of overland flow in a heavy rainfall event. The houses shown as blue are the blue spot buildings which will be flooded first. The model uses ArcGIS geoprocessing to determine the flooded areas and their neighbourhood watersheds. The DEM fill identifies the amount of rainfall that would be required to fill the depressions, by partitioning the BSM based sink-filling volume according to the watershed. The impact of the drainage network on flooding can also be predicted.

It is worth considering here that the model results are enough to identify critical flood-risk thresholds for single buildings. In the absence of building attributes, the best that can be achieved is to establish a worst-case scenario by determining the critical flood level for a building based on the ground floor level. This is, in fact, true for many houses, storerooms, shops, and workplace facilities. Though, it's not true for all houses. The actual flood level may be higher than estimates for buildings raised on high ground or above ground level. Conversely, the level may be lower than assumed for houses with basements. The BCSC house and housing register contains information about the building but does not include that information in the housing attribute table. It usually does not contain evidence about base heights for the building. Joining building features into the model will improve results.

Another component of vulnerability is that the water level for a building relies upon the building's precise vertical position inside the blue spot. Other factors being equal, a building at or near the bottom of a blue spot will be flooded sooner than a building higher up on its slope.

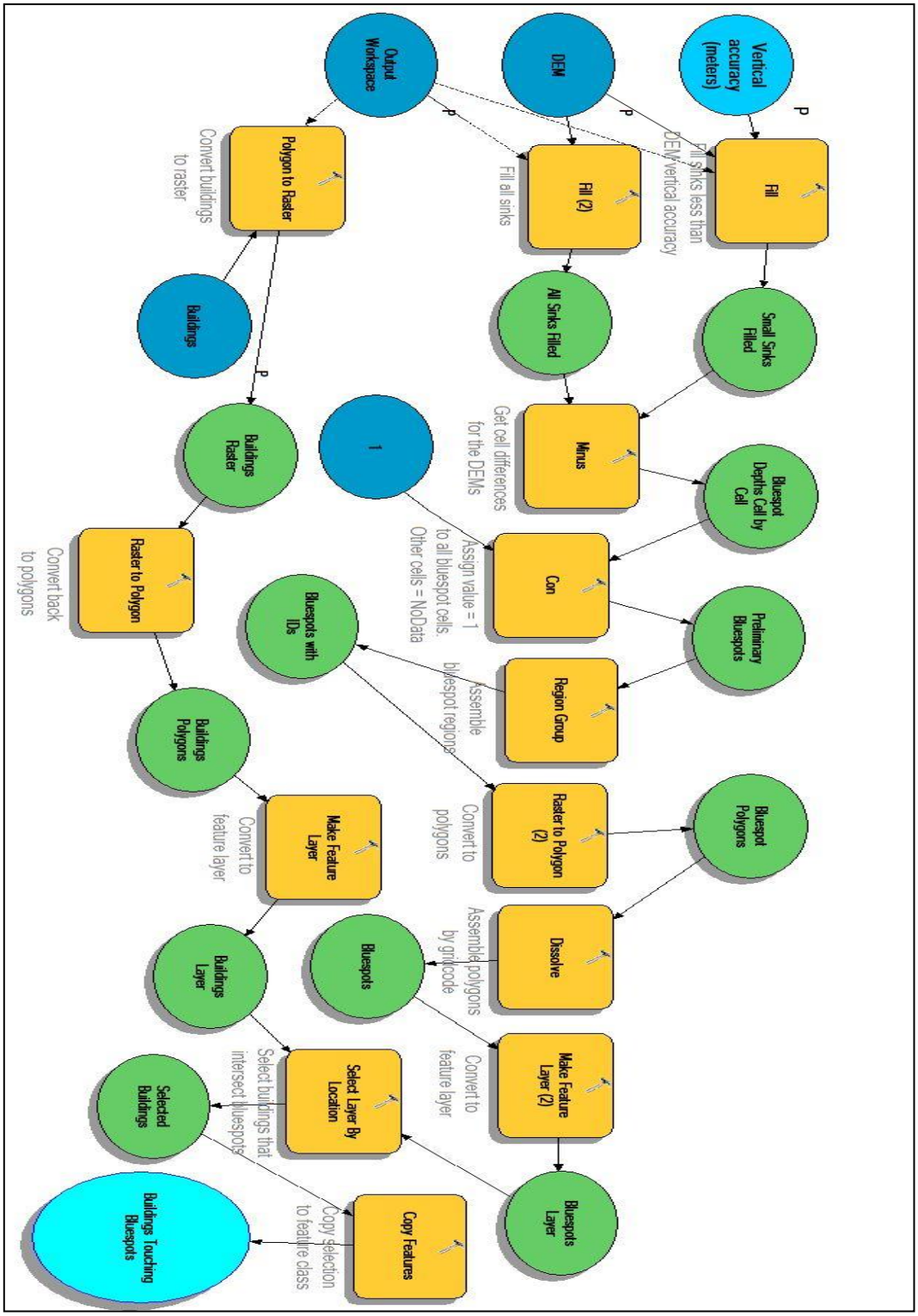
As discussed in the introduction of this Chapter, perfect runoff conditions are rare in real life, but in a cloudburst (extreme rainfall event), basic hydrologic assumptions can be relaxed. The ordinary flows levels that can be accommodated by the drainage networks may not have the required capacity during peak storms. At the point when this occurs, precipitation will create streams that in part or totally fill the blue spot. Note that the models presented here don't consider the diversion of surface runoff through drainage infrastructure.

An examination of the permeability of the surface, whether large parts of the local river basins are paved or not, could improve the risk assessment for individual buildings. A larger paved surface means a faster outflow. A raster data set indicating the percentage of the solid impervious surface for the Inverloch study area is included in the resource data geodatabase. Measurements of slope and length of flows within river basins would also be relevant to determine buildings that would have been hit first in a downpour.

6.3 Methodology for Blue Spot Modelling

This blue spot model (BSM) is implemented with ArcMap and the ArcGIS Spatial Analyst extension, four geodatabases including Inputs.gdb, outputs_bluestop.gdb, outputs_bluestopFillUP.gdb and resource.gdb and four toolboxes using model builders. Conceptually, the BSM has three main purposes:

1. It determines blue spots on the DEM.
2. It processes this result and the building's footprint outlines so the data is in the proper format for making a spatial selection.
3. It selects the buildings on the map that lies within or adjacent to the blue spots.



6-3: The overall workflow of the Blue Spot Model

(Based on a tool developed by Balstrom, 2018)

The main processes in the model builder are as follows:

- Blue spots are recognized by running the Fill geoprocessing tool on the DEM.
- The Minus tool subtracts values in the true DEM (Small Sinks Filled) from values in the filled DEM (All Sinks Filled) on a cell-by-cell basis.
- Con tool evaluates an expression as true or false for each cell.
- The expression "value> 0" is evaluated by the cell raster for a bluespot depth cell, which is true for any cell in a blue spot. These cells are given an arbitrary value of 1.
- Group blue spot cells individually into numbered regions based on fluency. An alternative is set to define diagonally connected cells as coordinates.
- The output raster dataset is bluespot with IDs

Dissolving the polygons on their grid code attribute merges the diagonally connected polygons with the bluespots they belong to. The final goal of this model is to find and select buildings within or adjacent to bluespots. The buildings are spatially compared to the bluespots using a specified relationship. In this case, the relationship is an intersection. Two features intersect if they touch, or partially overlap, or if one contains the other. Therefore, buildings will be selected if they are adjacent to bluespots, or if they are partly or completely within bluespots. The toolbox contains the following two geoprocessing models and the contents of the geodatabases and toolboxes are described in Table 6.1:

- The BSM identifies structures inside or adjoining the blue spots. The outcomes appear, with very coarse dimensions and illustrate which structures are at risk of a flood hazard in a storm. The model does not attempt to measure this hazard.

- The bluespot Fill UpValues model investigates and determines the BSM volume of each BSM and the region of its nearby watershed or catchment (the basin that channels water to it). From this data, the model calculates how much rainfall it would take to completely fill the blue spot. This model takes into consideration some positioning of flood hazard. The blue spot that requires less rainfall to overflow represents a higher risk flood hazard to buildings and infrastructure.

Table 6.1: The contents of the Blue Spot Model geodatabases

Name	Contents
Layers	Visualizing input spatial data.
Inputs.gdb	Starting data for models (Inverloch_LiDAR_point, DEM, Building, Raod)
Outputs_the BSM.gdb	Empty. Holds outputs of the classify the BSM (Bluespots, Buildings Touch BSM, Road Touch BSM).
Outputs_BSM FillUp.gdb	Empty. Holds outputs of the classify the BSM fill upvalues model.
ResourceData.gdb	An additional feature and raster data to explore and analyse.
BSM_Metric.tbx	Geoprocessing models (see Figure 6-3)
BSM_Metric_NoBuildings	Model versions for input datasets where building footprints are not available.

6.3.1 DEM-based Characterisation of Blue Spots using BSM

With ArcGIS hydrology tools, the DEM can be analysed to determine the blue spot regions, calculate their size and volume, and delineate areas that contribute water flow in a cloudburst.

In the pilot study area, it is important to analyse the DEM beyond the BCSC boundaries and include the nearby watersheds. To guarantee that all blue spot regions and watersheds are recognized accurately, the DEM for Inverloch was extended to include a 0.5-kilometre buffer. The Vicmap Elevation, Future coastal 1m DEM & 0.5m contours was derived from airborne LiDAR. Native Format: DEM-XYZ ASCII ESRI Grid ASCII Contours - ESRI Shapefiles, MapInfo TAB. The created DEM was inspected to identify the sinks and low-lying areas utilizing the cutting tool in the SAGA-GIS and assessing the impact of pit expulsion calculations on surface overflow reproduction. A DTM with pits removed is a precondition for hydrologic analysis. Two pit removal methods, the carving method and the filling method, are investigated in this study for three different geomorphometric areas. The input data are photogrammetrically measured DEM with a resolution of 5x5 meters. Šamanović et al. (2017) argued that choosing the correct calculation is critical, and suggested using a DEM without pits, including the minimum geomorphometric changes. The vertical precision of the DEM is critical for GIS based hydrological modelling. The methods used in this research enables

local organizations to evaluate the quality of the GIS databases, and use the GIS based hydrological models to improve flood risk management (Pourali et al., 2014b).

6.3.2 Blue Spot Model (BSM) and affected buildings

The limit of the examination region was constrained to areas covered by the LiDAR dataset. The DEM for the examination region was created based on the LiDAR data utilizing Inverse Distance Weighted (IDW) interpolation in the ArcGIS Geostatistical Analyst extension. In IDW only known z values and distance weights are used to determine the unknown areas. IDW has the advantage that it is easy to define and therefore easy to understand the results.

These models examine the DEM using hydrological tools to discover the BSM. At that point, the location of the blue spot region is identified in relation to existing structures and highlights the structures that are inside or nearby the blue spot region. These structures are at greater risk of being flooded. The geoprocessing model involves input data and tools organized as a workflow and runs as a single operation. The model process involves an input dataset (blue) connected to a tool (yellow) connected to an output dataset (blue) – see Figure 6-6. Input and output model elements are variables because their properties can be accessed and thus their pathnames can be changed. Conceptually, the model functions include the following three main steps, which are then explained in the following section:

- Identify the BSM Fill Up Values from the DEM.
- Use the Buildings layer so the information is in the best possible arrangement for making a spatial determination.
- Spatial determination Buildings layer on the guide that exist in or are contiguous to the BSM (ie identifying the Bluespots).

6.3.3 Identify the Blue Spot Regions on the Digital Elevation Model

This stage of the process involves identifying the blue spot regions on a predetermined DEM. Once this is done it is possible to spatially identify the structures that are inside or adjoining the BSM. These structures are at risk of flooding in a storm.

The blue spot regions are distinguished by running the BSM Fill up Values geoprocessing process twice on the DEM. The process is run once to fill sinks under 0.05 meters down, which are thought to be potential mistakes in the DEM. The output is the best DEM we can create. Next, the process is run a second time to fill all sinks to their pour levels. The output, a filled DEM without any sinks by any means, is vital for the following tasks.

The Minus operation subtracts values for the genuine DEM (little sinks filled) from qualities in the filled DEM (all sinks filled) on a cell-by-cell basis. The outcome is a raster dataset (the BSM is identified cell by cell) demonstrating the areas and profundities of the substantial sink, or the BSM.

With raster image analysis there are two types of cells (BSM cells and non-BSM cells) derived using the Con (restrictive assessment) tool. This tool assesses whether this condition is evident or false for every cell and allots a value to the cell accordingly. When this "Value> 0" for the Raster BSM cell heights, it is a Blue Spot and it is assigned a value of 1. Cells that have a "Value< 0" are not Blue Spot. The raster yield informational is collected using a cell by cell process.

The BSM cells have been identified, but they haven't been grouped in an intuitively meaningful way. It is normal to think about a contiguous set of blue spot cells encompassed by non-blue spot cells as a blue spot region. A first raster pixel value is allocated in this cell by cell process, followed by determining the blue spot value for every cell to create a blue spot and non-blue spot zones. Accordingly, the next stage is to group the blue spot cells into areas with the same number dependent on continuity. A choice is made whether to characterize cells diagonally associated corner to corner as adjacent.

The blue spot regions, which can be thought of as raster objects, are converted to a polygon feature class (the blue spot Polygons). The final output of the model includes data, which can be displayed and analysed with other feature classes.

6.3.4 Using the ArcGIS Dissolve Tool

In the raster-to-polygon conversion that produces the blue spot polygons dataset, raster cells that are diagonally associated with the BSM, which ought to have a place with BSM, are made as isolated highlights. Dissolving the polygons based on their cell value consolidates the diagonally-connected polygons with the blue spot region they are connected to.

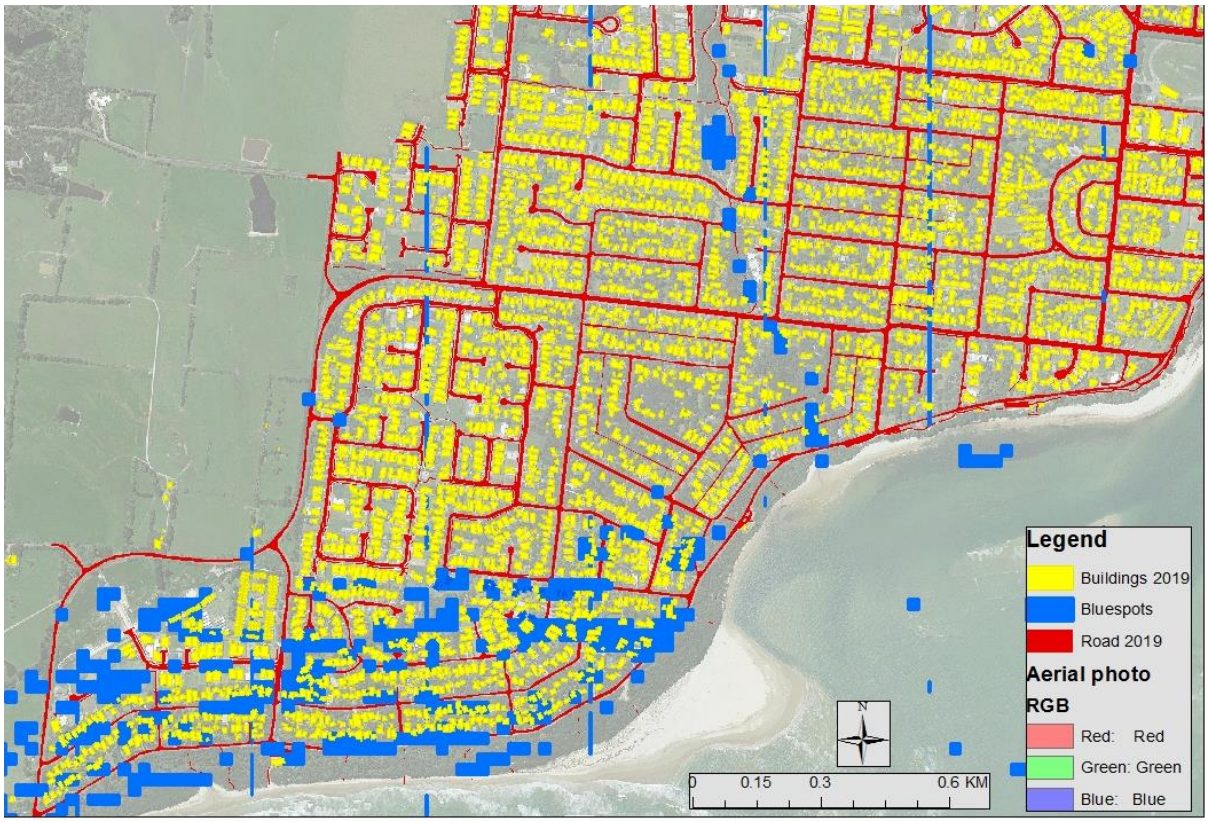


Figure 6-4: The BSM output for the Inverloch area.

6.4 Results of Blue Spot Modelling

The four important datasets are Buildings TouchBS (buildings touching blue spot) and Roads TouchRS (Roads Touching blue spot). Figures 6-4 and 6-5 show the location of the blue spot regions in the Inverloch area and affected buildings. In Figure 6-5 some vertical stripes are evident in the results from the BSM, which highlight potential errors in the DEM. The following section assesses these potential errors to see Figure 6-6.

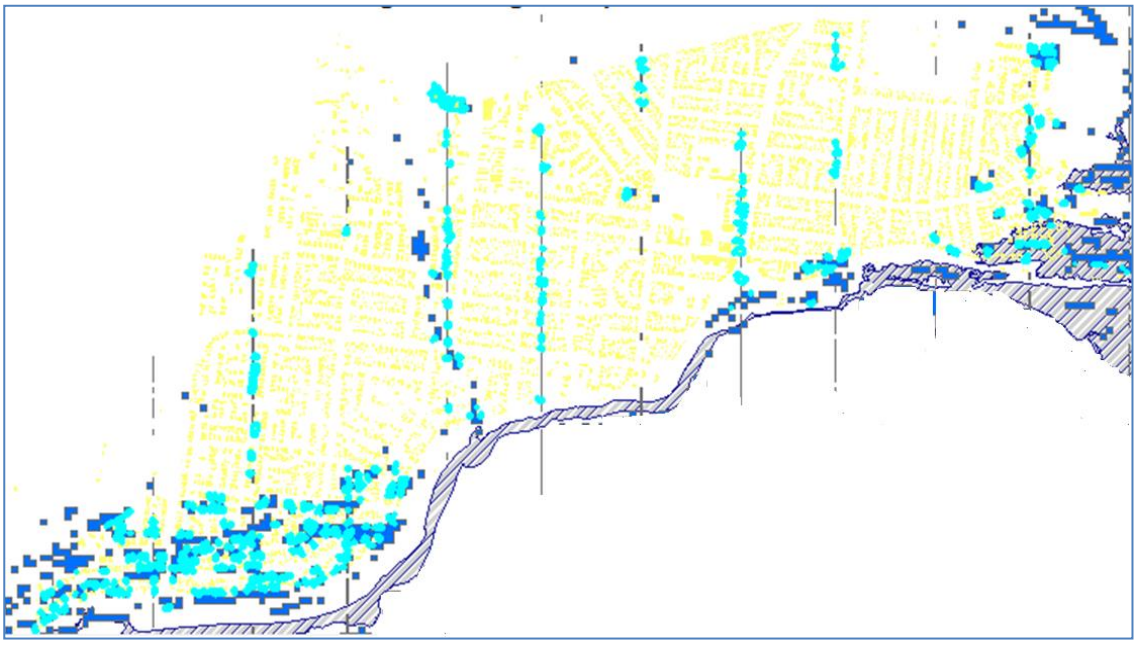


Figure 6-5: Building within the Blue Spot Model in the Inverloch area – Yellow denotes buildings, the Blue Spot areas are shown in dark blue, and the light blue are buildings that interest with the modelled Blue Spot areas.

As illustrated in Figure 6-5, over 467 buildings lie within or adjacent to the blue spot regions. From the attributes in the buildings layer, there are about 6165 buildings in Inverloch. This means that almost 7.9 % of the buildings have some level of flood risk in a cloudburst. The analysis has been done again based on DEM correction model vertical stripes in the results. After cleaning up the LiDAR data, different results were obtained. The updated results show that 345 buildings lie within or adjacent to the updated BSM. In other words, 5.6 % of the buildings will experience flood risk in a downpour. The intensity of the rainfall assumed that 90 millimetres of downpour fall in 60 minutes.

Figure 6-6: Road within the Blue Spot Model in the Inverloch area – red denotes roads, the Blue Spot areas are shown in dark blue, and the light blue are roads that intersect with the modelled Blue Spot areas.

As illustrated in Figure 6-6, over 212 roads lie within or adjacent to the blue spot regions. From the attributes in the roads layer, there are about 1034 roads in Inverloch. This means that approximately 20.5 % of the roads have some level of flood risk in a cloudburst. Analysis has been repeated based on correction DEM model vertical stripes in the results. After cleaning up the LiDAR data, different results were obtained. The updated results show that 149 Roads (14.4%) lie within or adjacent to the updated blue spot regions and will experience flood risk in a downpour.

6.4.1 Vertical Accuracy Validation Tools for LiDAR Data

LiDAR ground points were validated at various levels of minimum distance around each survey permanent marks (Ennenbach et al., 2018). The methodology adopted in this study prevents the gridding effect in the final evaluation.

To understand the degree to which gridding would impact the vertical accuracy, a direct regular IDW interpolation procedure and geo measurement IDW were utilized. The impact of

the geo measurement IDW and basic IDW in inferred DEMs exactness were investigated. Moreover, the autocorrelation between LiDAR ground points and GCPs have been evaluated utilizing an Average Nearest Neighbour (ANN) investigation proposed strategies for this study, successive least separation. The contrast between the LiDAR measured height and the rise as dictated by the PMs in the evaluated separation was around 0.5m at a 95% certainty level.

The difference between the LiDAR height and the value in the PMs was around 0.5m at a 95% confidence level. Therefore, the LiDAR ground point dataset can be utilized for flood mapping that does not require the vertical accuracy to be greater than 0.5m. The LiDAR ground point dataset does not contain enough vertical accuracy for drainage calculations, as a vertical precision of 10cm is required (Pourali, 2014). Figure 6-7 shows the results of a process for deleting duplicate points and problematic points, (-999, -0). Clean the raster of these duplicate and error points to have a smooth uncovered earth DEM. After utilizing IDW interpolation system and erasing blend devices, another BSM was created with the outcomes shown in Figure 6-7.

A B C

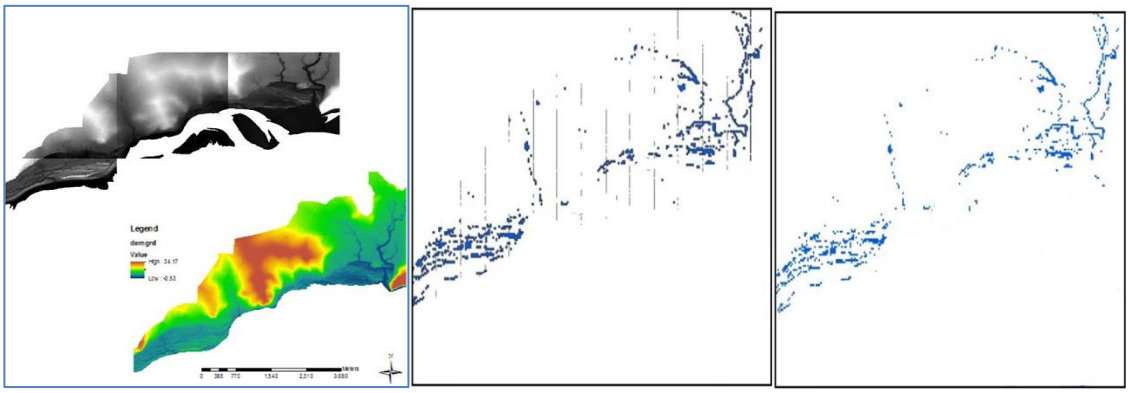


Figure 6-7: A: Delete duplicate and problematic point, merge LiDAR and create DEM. B: The vertical stripes error and C: the error-free model.

6.4.2 The Blue Spot Model (BSM) Analysis Results

After data analysis, buildings that are in the BSM attribute table can be examined to determine how many buildings and roads in the study area are at risk. As illustrated in Figure 6-6 there are many buildings within the BSM areas spread throughout the Inverloch area. However, floods can affect other types of infrastructure, as well as buildings and roads. Using this model, it is possible to add other infrastructure datasets, such as trails, and railways, to determine where they are in relation to the blue spot regions. Identifying the blue spot regions does not evaluate levels of risk to buildings and not all blue spot regions poses the same risk. How quickly the blue spot regions fill and overflows in a cloudburst depend on its depth, its flood risks, and the size of the catchment, or local watershed, that contributes rainfall to it.

6.4.3 Assessing Flooding Risk to Buildings and Roads

This section discussed how flood hazard risk to buildings can be assessed, along with how much precipitation is needed to fill each Blue spot region up to its pour point. This data will help improve the assessment of flooding risk to structures. This model has been developed for situations in which building footprints may be accessible or not accessible. The model identifies blue spot regions on a DEM and computes how much precipitation is needed to fill up a blue spot region in a downpour. This data improves the assessment of flood risk for a building situated in a blue spot region. A building in a blue spot region that fills up rapidly has a higher level of flooding risk than a building in blue spot region that fills up gradually (Balstrøm and Crawford, 2018).

The model is based on the hydrological assumption that each blue spot region in the landscape has a catchment area in which this region contributes only to the flow of that blue spot region. It can be determined how much rainfall is needed to fill the blue spot region by calculating the capacity of the blue spot region and the area of its watershed. For example, if a blue spot region's volume is 500 m^3 and its watershed is 10,000 m^2, the rainfall needed to fill the blue spot region to its pour point is 500 m^3 / 10,000 m^2 = 0.05 m = 50 mm (Balstrøm and Crawford, 2018). In fact, not all the rainfall that falls in the watershed streams into the blue spot region because ideal run-off situations don't exist. However, the run-off conditions in a storm are near perfect. The water balance condition P = I + E + Ao + Au + Q expresses that precipitation

(P) is equivalent to the interception by vegetation (I) plus evapotranspiration (E) plus surface run-off (Ao) plus soil infiltration and sewer system (Au) plus quantity of local supplies (Q). In this specific situation, a local store implies blue spot region (Balstrøm and Crawford, 2018).

For this process, the approach used by Balstrøm and Crawford (2018) was implemented. In a cloudburst, blockages, dissipation and soil infiltration can be viewed as zero. The maximum capacity of Danish drainage system in local locations is around 40 millimeters of downpour per day. Focussing on 1 hour of precipitation and if the day by day limit is 60 minutes, the value for the soil infiltration and sewer system (Au) would be set to 40. Surplus runoff (Ao) won't be a factor in the condition until after the BSM fills up. For the fill-up values, the equation can therefore be streamlined to $P = 40 + Q$ or $Q = P – 40$ millimeters for every hour. If 90 millimeters of downpour falls in 60 minutes, the sewer framework will divert 40 millimeters, while 50 millimeters will stream into the BSM—filling it either somewhat or totally. If BSM is filled to its pour point, the overflow (Ao) will enter the following downstream sink, lake, waterway, or ocean (Balstrøm and Crawford, 2018).

While this model provides an improved assessment of flooding risk, there are limitations to this approach as overflow downstream of the blue spot region isn't considered. Nor is the height of the structures inside the blue spot region. For instance, if a building is situated close to the base of the blue spot region, it could be flooded before the blue spot region completely fills up. Further, underground structures such as basements are not considered (Balstrøm and Crawford, 2018).

As well as identifying the blue spots in the BSM, it computes their volumes and watersheds. This data is useful in calculating the amount of precipitation expected to fill each blue spot region. Many of the workflow model procedures are operations for table manipulations: including adding fields, joining fields, and computing field values. The BSM analyses the amount of water that is needed to fill each blue spot, thus making it possible to assign relative degrees of flood risk (See Figure 6-8).

The colours in the legend for the fill-up values start at 40 millimetres to represent the drainage network limit. If values of 0 - 20 mm exist in the Fill-up field, they will be marked as 40 - 60 mm when the symbology is connected. Add also field to the BSM touching buildings and calculate its values to [Fill-up] + 40.

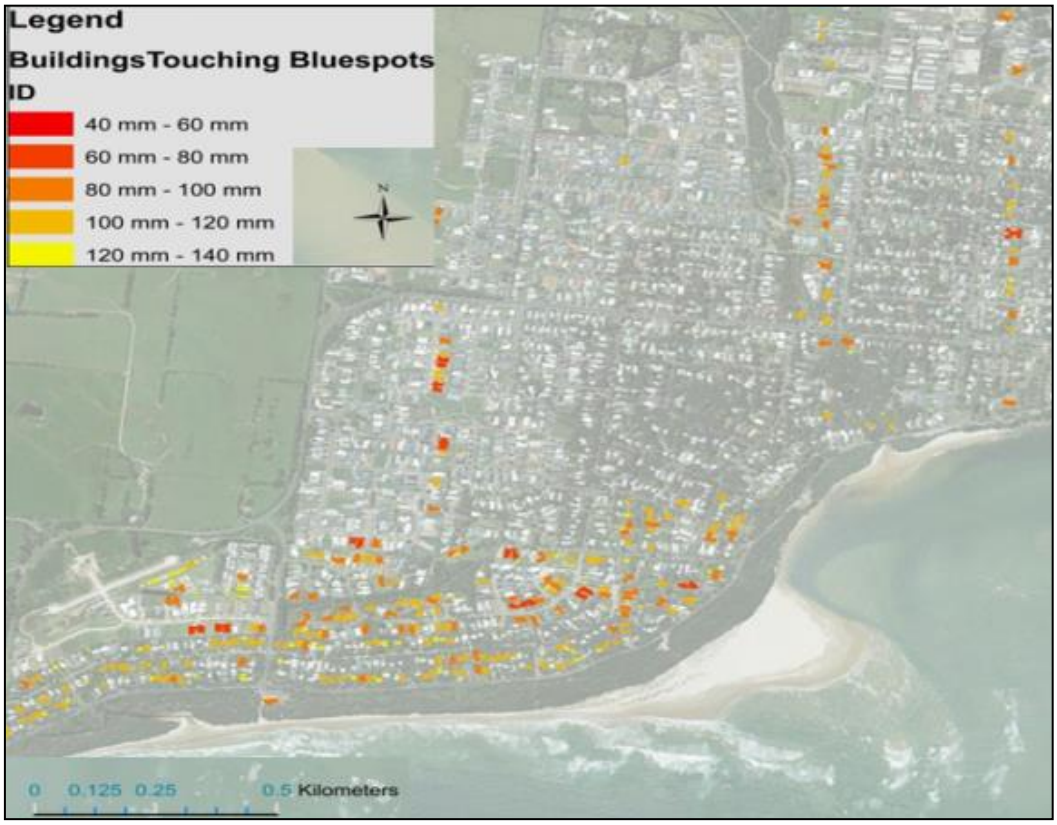


Figure 6-8: Assess flood risk to buildings Inverloch area

BCSC experienced large precipitation in August 2012, following previous storms. Phillip Island experienced over 90mm rain, including 55mm in one day, nearly achieving the normal September precipitation in less than 24 hours. It was likely that blue spot regions associated with the top 2-3 risk categories (Coloured as red, dark orange, Orange in Figure 6-8) would fill up. This heavy rain did caused flooding across the region.

Figure 6-9: Assessing flooding risk to buildings in Wreck Creek, Inverloch

Some buildings in Figure 6-9 appear susceptible to flooding are not highlighted. While there may be a blue spot region in those areas, they are not highlighted as being at risk as the blue spot region fill up volume is in excess of 140 millimeters rain balanced. It's very unlikely that these blue spot regions would flood. The calculations predict the whole blue spot region would not be filled, yet this isn't generally the situation. Some blue spot regions are lasting water bodies, for example, Wreck Creek in Inverloch zone.

Further analysis is required to find out how many buildings are within blue spot regions of different risk levels. BSM be selected in the highest risk category with the attribute query "FillUp >= 0 AND FillUp <= 20" on the BSM Buildings level. Spatial building selection that intersects the selected set of the BSM. It is possible to add the watersheds layer to examine the relationship between blue spot regions and the areas that contribute flow to them. Precipitation affects the lower parts of infrastructure such as buildings and roads. Avoid flooding on the road networks, flooding leads to traffic jams, making roads unsafe and damaging the road surface.

Blue spot models can be used to perform accurate water flow calculations considering the cavities and dips as well as other surface conditions. These models produce a "blue spot map" that shows where and how intensely the road network will flood for a given flood. These models identify the location of the watercourse and develop guidelines for how to reduce flood exposure. The result is a screening method that the municipal environment department Planners, road authorities and other interests can use. While the BSM has been incorporated into the computations, the variation in assessment of future flood risk is difficult due to climate variation.

This research shows a unique approach to the BSM to describing the urban overland runoff under a heavy rainfall scenario in an innovative way. The key finding from this case study is that a high-resolution modelling methodology is important. Furthermore, the distributed data model creates a feasible data schema for subdividing the scene data under basin from hydrology recognitions empowering it to fit into genuine hydrology conditions.

It is also integrated with coastal urban heterogeneity distribution models, opening an entryway to even more extensive inclusion of hydro-displaying related datasets to be included. Also, unlike a ‘one for all’- modelling approach, the modified sub-model group method makes it possible to produce diverse individual stormwater model depending on different modified target rainfall events and flooding objects. It provides a possible modelling approach to adapt to the dynamic world. Also, multiple hydrological examinations were connected in the model. Not all sub-models generated from the entire drainage basin provide a reliable boundary for hydrology modelling, the small scale hydrological changes, achieving improved flooding connectivity between coastal and other areas. The automatic process of the Blue Spot model with little manual input A programmed method in BSM with minimal manual information sources requires reduces analysis time when developing the input hydrological model.

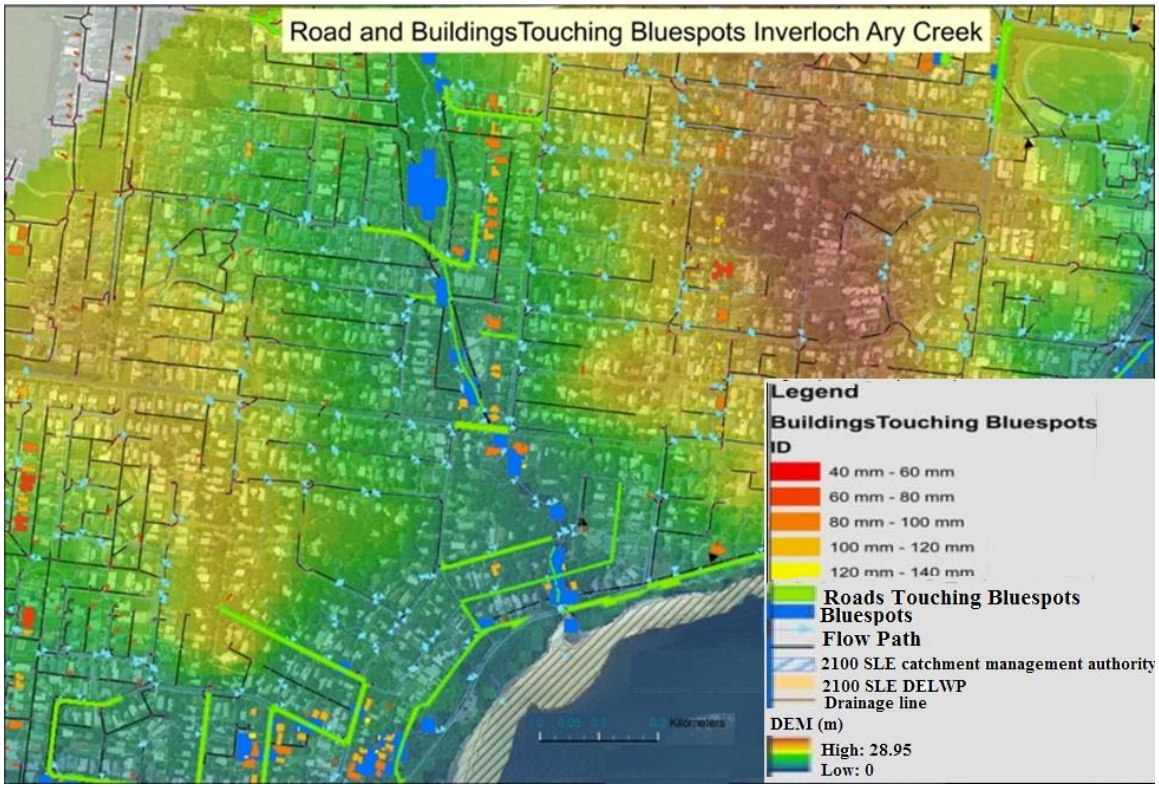


Figure 6-10: Roads and Buildings Touching Blue Spots in Ayr Creek, Inverloch.

6.5 Chapter Summary

In this Chapter, the Methodology for producing a blue spot map for Inverloch that identifies low-lying areas blue spot regions with no natural drainage was presented. In a cloudburst event, the blue spot regions may fill up and overflow, damaging buildings and roads that lie within and adjacent to them. BSM tools will support flood-risk land use planning at the local level and allow the usage of new forms of information to assist in the decision process.

The results presented in this Chapter involved new applications of geoprocessing to derive the blue spot regions and their local watersheds. The fill-up qualities are determined by partitioning the BSM volume by the local watersheds. It is then possible to assess how much flood water can be accommodated by the drainage network. These results, however, need to be viewed with some caution. In Australia, when storms are heavy from a specific wind direction over a couple of days, many low-lying coastal areas are at risk of getting

flooded. Thus, research questions two, three, and four listed in Section 1.3.2 focus on which tools are useful for coastal drainage analysis. This is useful for local government planners to understand areas that might be threatened due to a sudden or a long term flood impact.

This Chapter began with an analysis of the relevant literature. Based on that analysis, the research model allowed assessment of flood-risk thresholds for infrastructure. However, without building attributes, the best can be done is to establish a worst-case scenario by assuming that the critical flood level for a building is at its base height. Flood levels might be higher than accepted for structures with high building levels or structures that are raised above the ground. On the other hand, the dimension might be lower than expected for structures with storm cellars. The BCSC property department has data about whether structures have cellars, yet that data is excluded in the building attribute table. It does not have data about basements for structures. Incorporating infrastructure attributes into the model would improve the outcomes.

Since a hydrological model depends on characteristics of a given study area, no specific model of flow direction is universally applicable, which is the fundamental step in the hydrological models integrated into GIS. The implicit assumption is that the DEM generates a reliable flow direction surface, and this assumption is more valid for higher resolution DEM. Another component of uncertainty is that the water entry level for a building depends on the building's actual vertical position inside the blue spot region. Different factors being equal, a building at or close to the low point of a blue spot region is going to be flooded before a building on its high point.

As discussed in the introduction to this Chapter, perfect outflow conditions are rare, but in a downpour, basic hydrological hypotheses change. The normal infiltration capacity of the soil becomes irrelevant and the drainage systems can reach maximum capacity very quickly. When this happens, rainfall will turn into rapid overland flows that partially or fill blue spot regions. BSM deployed in this study doesn’t consider diversion of surface runoff

through drainage ditches or other channels. The research also considered some improvements to the BSM's Fill up module.

An examination of the solidity of the surface if the large parts of the local river basins are paved or not, could improve the risk assessment for individual buildings. An examination of the permeability of the surface, whether the large parts of the local river basins are paved or not, could improve the risk assessment for individual buildings. More paved surface means faster outflow. A solid impervious surface percentage raster data set for the Inverloch study area would be useful. A study of the slope and length of flows within the river basins would also be relevant to determine which buildings would have been hit first in a downpour.

This Chapter assesses flood risks for residential areas caused by cloudbursts. The focus has been on developing models to estimate the flood risk for an existing building or planned new developments. The next Chapter will present the methods used in identifying infrastructure at risk from SLR flooding using ArcGIS and FME.

Chapter 7

7 Identifying Infrastructure at Risk from Sea Level Rise Flooding

7.1 Introduction

In this Chapter, GIS-based hydrological modelling for coastal flood risk from sea-level rise (SLR) is described in order to answer research question 5 (section 1.2.2):

- RQ5 How does a spatial decision support system help to identify infrastructure at risk from SLR flooding?

SLR may occur due to changes in global sea levels and tectonic subsidence of land surface over many years but may also occur due to sudden stowage of seawater in creeks, inlets, sounds and lagoons caused by long-lasting storms with uniform wind. In Victoria, when storms are heavy from a specific wind direction over a couple of days, many low-lying coastal areas are at risk of getting flooded. The prediction of climate change presents local governments and coastal communities with complex challenges and difficult decisions, particularly about flooding impacts on public and private infrastructure. Councils must provide leadership by ensuring they understand the risks associated with predicted SLR scenarios, as well as high-intensity rainfall events and associated overland flows, so that adaptation strategies can be put in place to minimise risk.

As discussed earlier, the BCSC is taking a proactive role in the development of adaptation tools to assist strategic planners and communities to understand what climate change impacts may occur in the future. With a better understanding of the natural landforms and geomorphology, the Council now can better understand the characteristics of water flows – whether from SLR or storm events or both. As most of the urban settlements in the study area are close to the sea, the combined effects of SLR and storm events will test the performance of the underground drainage system. The application of methods presented in this research will also provide the opportunity to better plan for future urban development through having a strategic view on the wider catchments including the rural/urban interface. Other benefits include the development of appropriate WSUD features to replicate the natural drainage system and to control water quality flowing off surrounding agricultural land. The availability of the Future Coasts LiDAR data will allow the local

government to develop cost-effective solutions for the identification of overland flow paths, refined drainage catchments, and running interactive SLR scenarios. Coastal communities in the Inverloch area face an increasing scale of flood risk due to SLR.

The infrastructure at risk under different SLR flood scenarios can be assessed in the ArcGIS Spatial Analyst extension to assess the vulnerability of infrastructure and assets. This research used LiDAR base flood polygons to select structures that intersect flood polygons and can calculate the value of property, road and other infrastructures at risk, using council asset data.

Considering the dynamics of coastline change, high-quality timely and accurate information can be used to describe the coastal conditions (Fitzgerald et al., 2008; Gutierrez, Williams, and Thieler, 2007; Leatherman, 2001; Leatherman, Zhang, and Douglas, 2000). However, conveying the risks related to SLR remains a challenge (Treuer, 2018).

To accurately identify and delineate land that is vulnerable to SLR, the challenge is to understand the physical reaction of coastlines to anticipated SLR. The underlying coastal tide processes and the relations between them should be understood. The topography is a key dataset and up-to-date high-resolution and high-precision elevation data is needed to model the coastal area. Maps that define areas subject to SLR often called vulnerability maps are very useful for planners and managers who are responsible for mitigating the risks. However, many of the maps produced to date are basic images derived from coarser elevation data and do not differentiate between the physical processes driving coastal change (Schneider and Chen, 1980, Rowley et al., 2007).

Using GIS to map the spatial extent of potential SLR is a typical technique for attempting to identify hazards in coastal areas. This type of GIS generated maps are regularly incorporated into assessment reports.

While the quality of input data is sometimes questioned, there is a little comment on the inherent vertical uncertainty of elevation data. However, some users provide general caveats on data limitations on maps indicating they should not be used for detailed planning.

This research on the study area mainly focuses on risks of SLR, coastal erosion and extreme weather events affecting human settlements, infrastructure and industry located within the coastal area. There are extensive areas with low-lying coastline within the BCSC. Some of these areas are already subject to inundation from the sea during extreme storm tide events. The increase in SLR projected to the year 2100 will result in a significant increase in the extent, frequency and depth of coastal inundations within BCSC.

The purpose of the Land Subject to Inundation Overlay (LSIO) is to identify land affected by riverine flooding and land that will be affected by coastal inundation based on SLR projections through to 2100. The aim of applying the LSIO is to trigger further analysis by the relevant referral authority to consider whether a permit should be granted for a proposed development. The primary aim of the research is to identify the potential coastal flooding risks to BCSC communities. The high-resolution elevation data will improve the accuracy of flood modelling and the ability to understand the current and future risks to infrastructure and communities. Therefore, this research creates a GIS tool for council planners that can provide an overview of areas that might be threatened by a sudden or a long- or short-term climate impact.

Sea level is not rising uniformly around the globe mainly because the earth is a geoid with a molten core, and it changes its shape due to gravitational forces. To monitor the sea level changes around the Australian coast, the Bureau of Meteorology (CSIRO and BoM) maintains the Australian Baseline Sea Level Monitoring Project (ABSLMP). This project has been monitoring sea levels with high accuracy tide gauges at 16 locations around the Australian coastline since the early 1990s.

One of the ABSLMP monitoring stations is located at Stony Point in Western Port. This gauge became operational in January 1993. Since then, this gauge has measured an average increase in mean sea level of 3.5 mm per year, through to 30 June 2014 (BoM, ABSL MP Monthly Data Report June 2014). This shows that the current rate of SLR in the region is consistent with the globally averaged value provided by the University of Colorado's analysis of the satellite altimeter data for the corresponding period (Noone and Economic Perspectives, 2013). The key points to note about the historical rates of SLR are that (Mote et al., 2008):

- SLR is happening now. It is not just something that will occur at some point in time in the future (e.g., 2040, 2070 or 2100).
- The current rate of global SLR is approximately double the average rate that occurred over the 20th Century.
- The current rate of SLR in the Bass Coast region of 3.5 mm per year is consistent with the global trend.

Warming of oceans is a much slower process compared to atmospheric warming, and therefore, any rising trend in oceans is expected to have longer runs.

The aim of this research is to demonstrate coastal flood management using a LiDAR based DEM to distinguish inland regions that are not hydrologically associated with the sea. Using an accurate elevation model, these inland regions can be identified for exclusion from areas of inundation since they are not hydrologically associated with seawater. This approach to identifying hydrological availability using a LiDAR DEM isn't new (Poppenga et al., 2010). In this study, LiDAR data is used for improved hydrological modelling. coastal inundation mapping, and identification of locations where seawater and inland water meet or connect.

This research evaluated each inland region to identify the parts that could be affected by coastal inundation. This demonstrates that further investigation of hydrological data using

LiDAR DEM is required for coastal inundation assessment and action to reduce flood risk (see section 2.9).

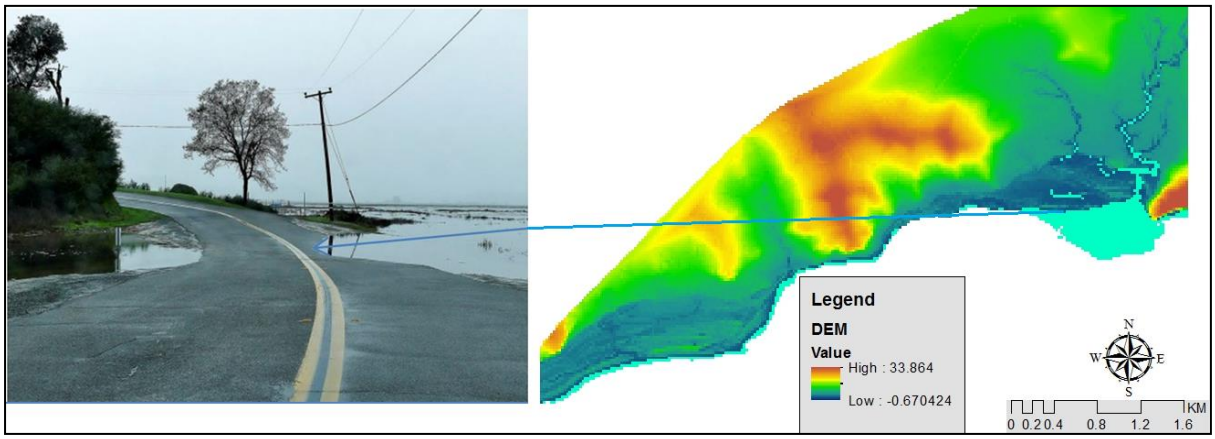


Figure 7-1:Flood delineation (light blue) representing LiDAR elevation values of less than 1 m overlaid on a high-resolution LiDAR shaded -relief.

7.2 Methods for Identifying Infrastructure and Buildings at Risk

7.2.1 Aims, software used, and data required

The flood models in this research were developed to predict the Inverloch coastal areas that are vulnerable to flooding during a storm if the way the coastal landscape is represented by a DEM will not be altered during the event. Three versions of the flood assessment tool for identifying infrastructure and buildings at risk are available: a) the first allowing for adding a dam represented by a digitized polyline having a constant level defined by the maximum elevation. Elevation is detected in the DEM underneath the digitized line segments, b) the second does not include this polyline feature and c) The third helps to identify infrastructure at risk from SLR flooding. The models are designed for ArcGIS Desktop 10. X with the Spatial Analyst extension. The only data required is a projected DEM, buildings, roads and other assets.

SLR may be modelled as a surface from the sea towards land until a non-passable barrier is reached. The barrier is defined by using the ArcGIS SetNull tool to assign NoData values to all cells in the DEM ≥ the modelled sea level and assigning a value of 1 to all cells below

that level. To initiate the flood analysis using the Spatial Analyst cost distance tool, a point at sea must be identified as the source cell. The flood is simulated through multiple iterations with a constant increase of the sea level, for example going from +0.25 to 2.5m in increments of .25m.

7.2.2 The iFloodModel

As illustrated in Figure 7-2, the main iFlood model requires a point at sea and a dam and the specification of the initial sea level, the sea level incremental values and the number of sea level iterations. Two feature class schemas have been prepared for the digitized point at sea (Ocean Point) and the digitized dam.

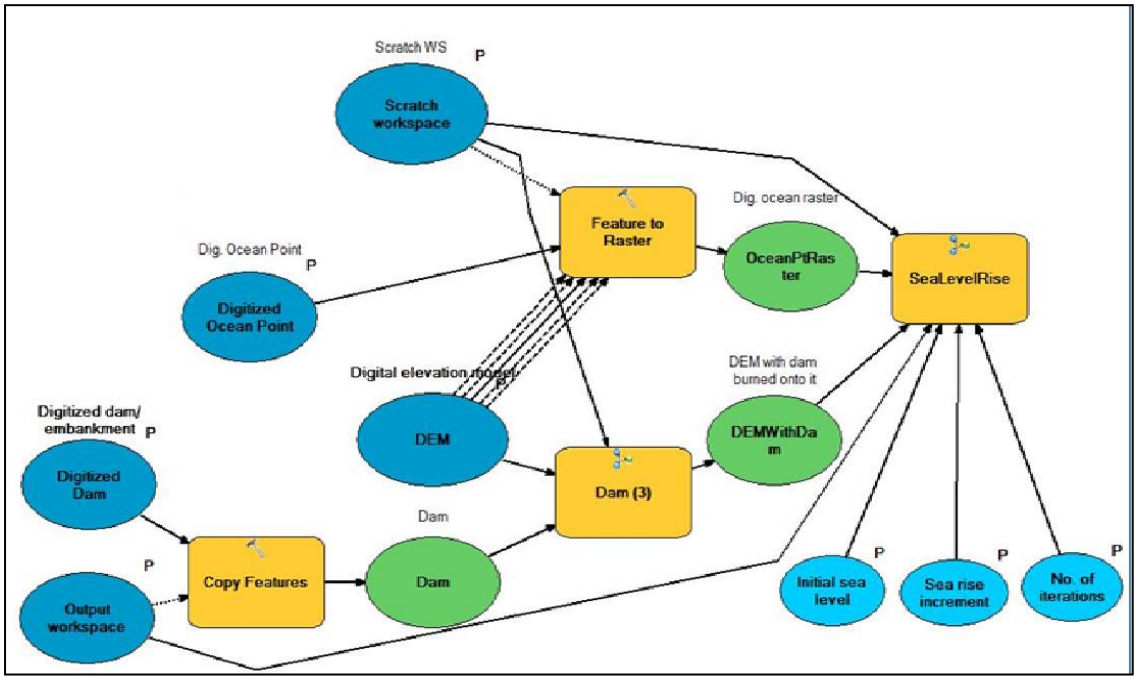


Figure 7-2: The iFloodModel (Adapted from Balstrom, 2018)

This iFlood model illustrated in Figure 7-2 simulates the impact of flooding caused by temporary water stowage or a constant SLR due to climate change. This version creates a dike by digitization and afterwards, the iFlood model is created. The dike's upper level is set at coastal Z-level (ground) based on the maximum elevation. Also, the ocean floor elevation must be digitized in the flood model.

7.2.3 Execution of the iFloodModel without the Digitized Dam

To simulate an increasing flood caused by temporary sea stowage or a steady SLR due to climate changes, a point located at sea must be digitized to initiate the flood. The flood's initial base level, the incremental SLR and the number of iterations (sea levels modelled) must also be defined, and the resulting rasters are saved in the outputs file geodatabase. The model builder process is illustrated in (Figures 7-3 and 7-4).

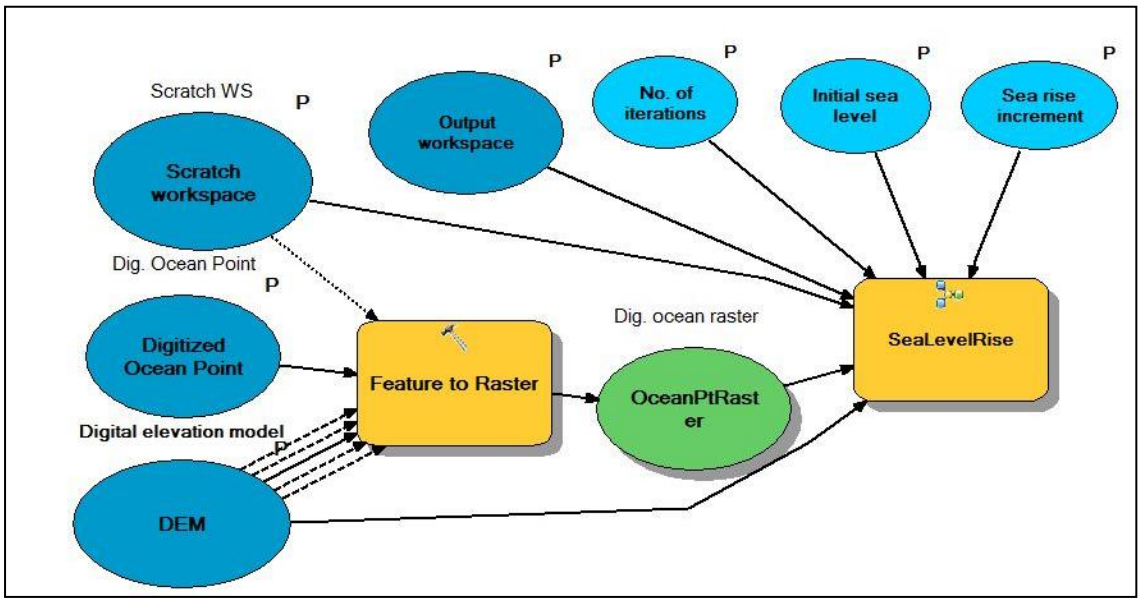


Figure 7-3: Part of the iFloodModel that creates a digitized dam in the initial DEM. The 'no dam' version of the iFloodModel is executed in the same way as the full iFloodModel

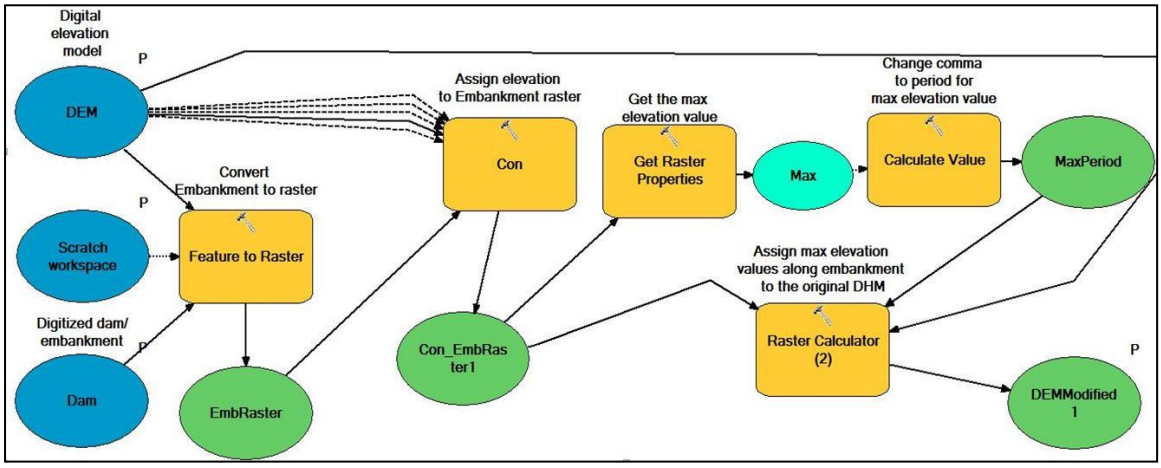


Figure 7-4: Workflow for digitizing a damwall or embankment as a polyline and burning the polyline onto a DEM. The dam's level is assigned as the maximum. DEM value along the digitized damwall.

The three images below show the modelled flood levels and illustrate the impact of the established dam (if present), see Figure 7-5. Red line is Dam and blue colour water level.

A B

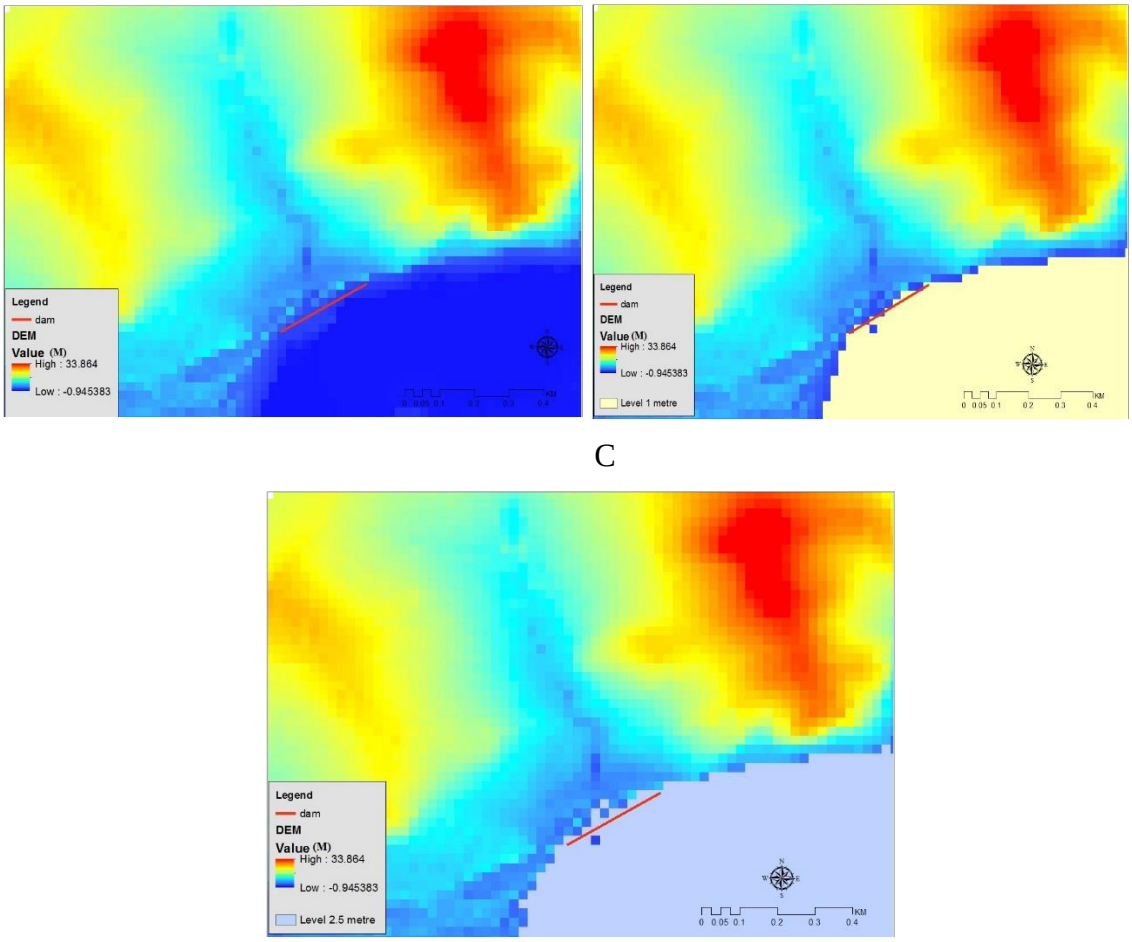


Figure 7-5: DEM with a 0.9 m high dam wall added (A), which is flooded with modelled SLR of either 1.0 m (B) or 2.5 m (C) above sea level.

When the model in Figure 7-5 is completed, it is important to refresh the geodatabase created by ArcGIS (Output.gdb). All modelled sea level outputs are named 'Level xxxCm', where xxx is the sea level value in centimetres. The next step is to drag and drop all outputs from the geodatabase into ArcGIS, and then organize the layers so the 250 cm output is positioned right above the loaded DEM, insert the 250 cm output on top of that one. The last step is to create the digitized dam as the top layer (if present), Figure 7-5 (B) convert 100 centimetres to 1 metre.

7.2.4 Execution of the Sea Level Rise Flood Model

To model coastal areas that would be inundated based on a mean SLR using raster dataset and Map Algebra, flooded cells are identified, classified, grouped, and converted into polygons. The elevation raster is essentially a grid of cells, each cell containing an elevation above mean sea level. If the SLR is 2.5 meters, this must be subtracted from the current elevations that are in the raster assuming that anything below zero is negative. The area of the coast that will be flooded can be estimated by a below water scenario from a non-breaking space (nbsp) (Balstrøm and Crawford, 2018). Figure 7-6 shows a workflow to calculate the areas affected by a rise in sea levels. Ocean point raster must be present before the model is executed.

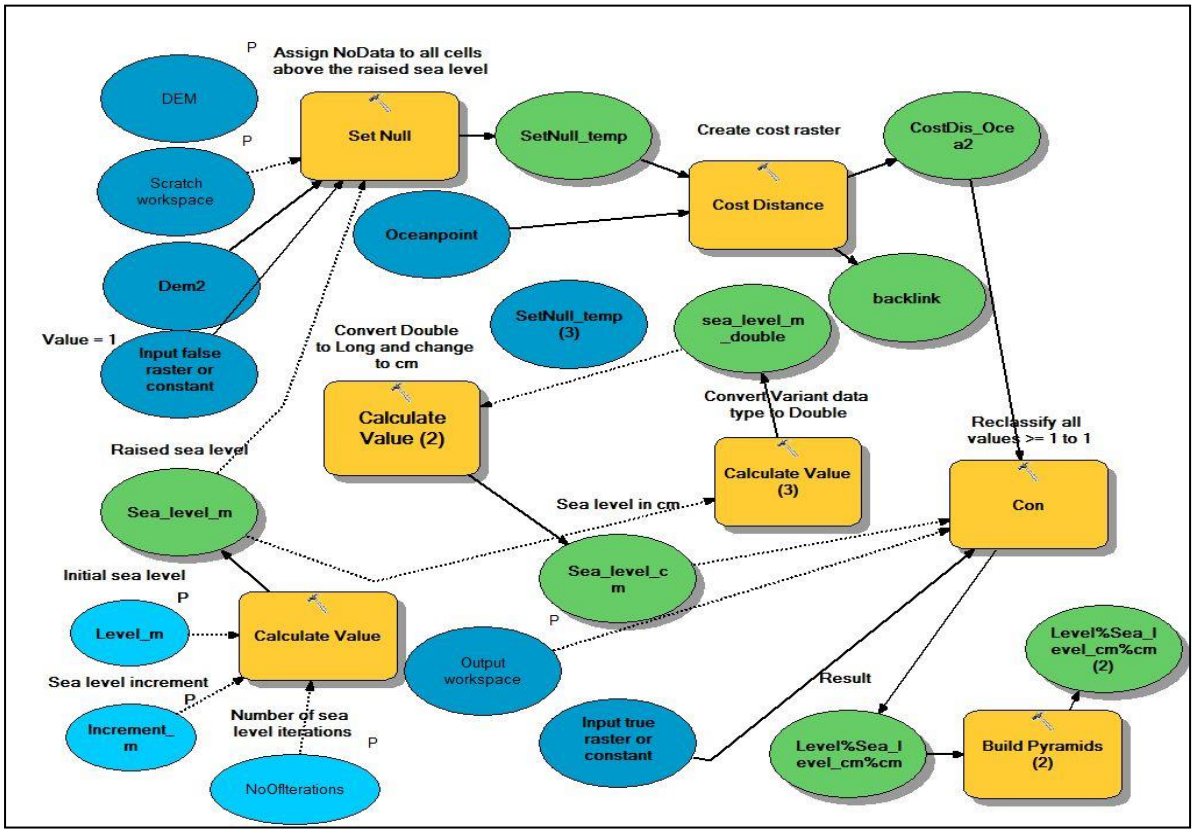


Figure 7-6: Model to calculate the land area inundated due to SLR.

Using LiDAR to predict SLR output is shown in Figure 7-7, showing the scenario for 1 meter of SLR, flood event in the year 2100 in Inverloch. The dark blue colour represents the lowest area where assets are vulnerable. Adaptation actions in this area would include

installing a cyclone barrier, elevating a road, and building dikes, each of these actions would provide some protection to the vulnerable areas.

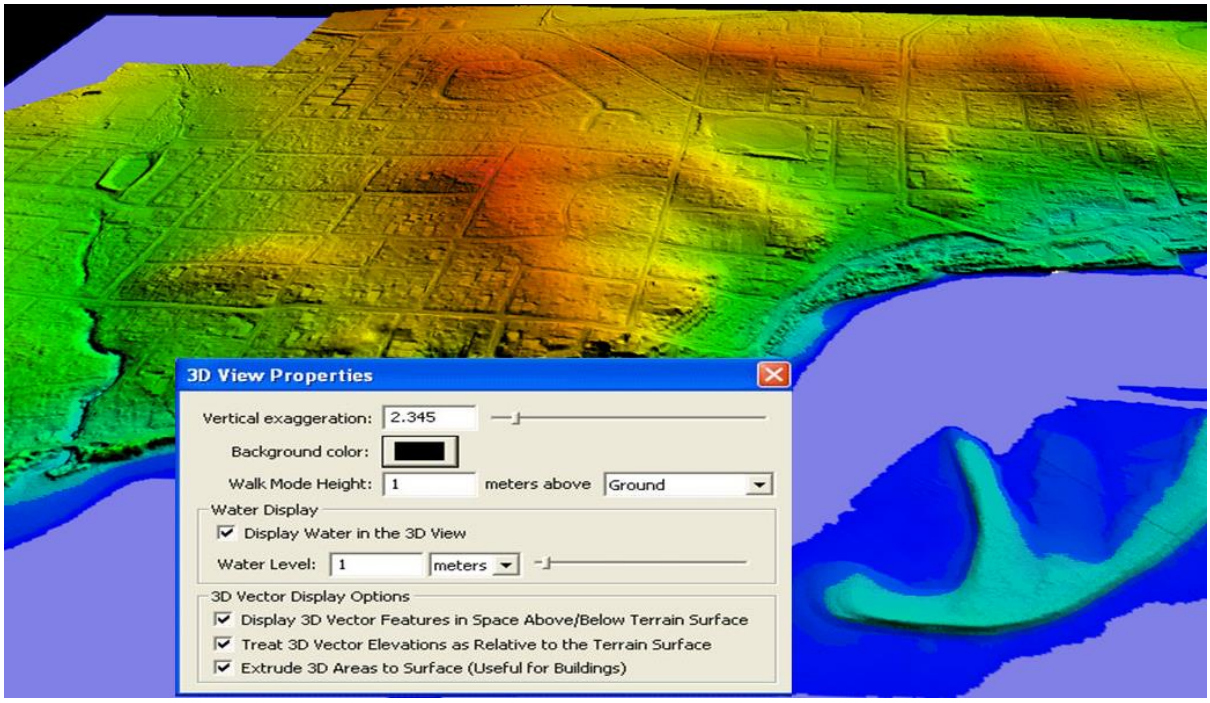


Figure 7-7: Using LiDAR data to Predict Sea Level Rise (blue as watercolour)

The IPCC 4th Assessment Report presents three scenarios for SLR between 2030 and 2100 and the related Victorian scenarios are summarised in Table 7-2 below.

Table 7.1: Three IPCC 4th Assessment Report SLR scenarios, 2030-2100 (metres), Victorian coast.

Year	Scenario 1 (B1)	Scenario 2 (A1FI)	Scenario 3 (High end)
2030	0.13	0.15	0.2
2070	0.3	0.5	0.7
2100	0.5	0.8	1.1

Figure 7-8 below illustrates that the population and economy will be affected near to the coastal area in a historical 1-in-100-year inundation event and then explores how these may change under different scenarios of settlement adaptation at present, or in 2030, 2070 and 2100.

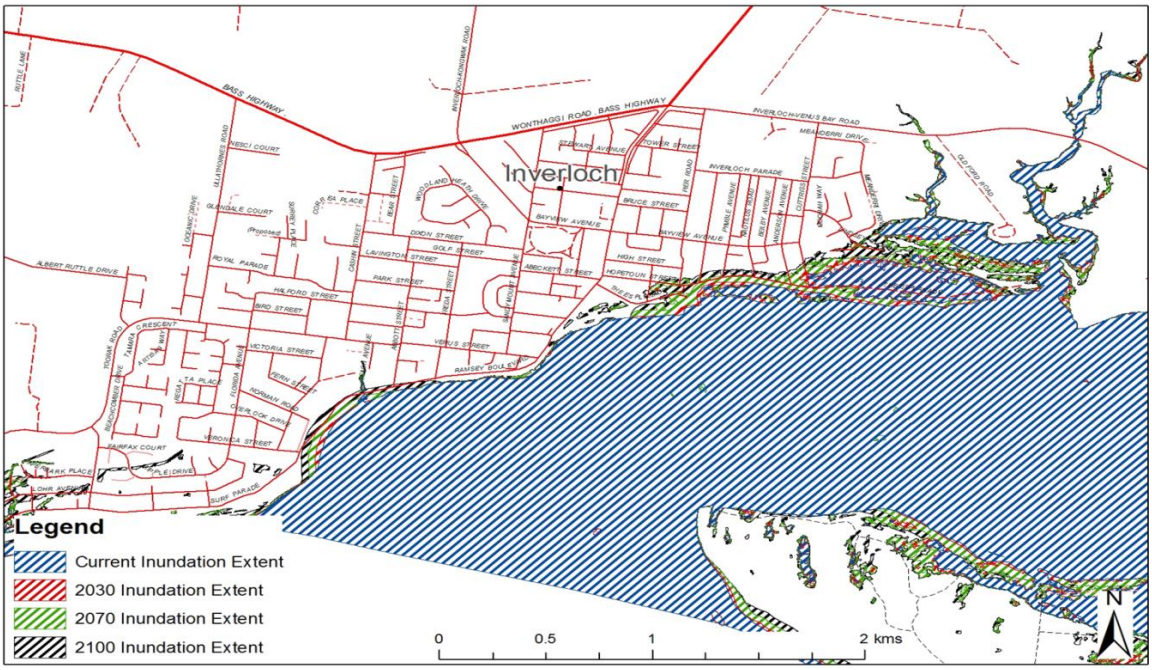


Figure 7-8: The spatial impact of the three scenarios developed by CSIRO for SLR between 2030-2100

(compared to 1990).

These values have been adopted in this thesis which includes models for Scenario 3 (the high end) rise of 1.1 metres.

7.3 Infrastructure at Risk from Sea Level Rise Flooding

Infrastructure, in this case, refers to physical structures associated with critical community services and other local government facilities such as buildings. This includes built infrastructure related to transportation and communication, water and power and sensitive public infrastructure such as waste disposal areas, which the community normally relies on but may cause a contamination risk if flooded.

Identification of infrastructure at risk under different SLR flood scenarios can be done with GIS operations such as overlay, intersect and calculation of attribute values, in two ways—the first is identifying infrastructure that intersects flood polygons, and the second is the identifying infrastructure that falls completely within flood polygons. The choice between

these two methods depends on the degree of overlap and the nature of the infrastructure. Both methods were examined in this research.

The data required for this analysis includes polygons of the flood prone areas and the infrastructure layers. Three polygons featuring classes of flood prone area were generated from a raster elevation dataset. Each infrastructure layer should be clipped to the neighbourhood in order to minimize processing time as well as to allow GIS to calculate the percent of infrastructure within the neighbourhood that would be affected under each flood scenario. In this study roads, buildings and land use were identified at risk. The purpose of this study is to examine the infrastructure at risk under the worst-case scenario which is a flood height of 2 m above mean sea level (i.e. more than 1.1m IPCC Scenario 3). The initial step is the identification of the roads that would be affected by the flood. Selecting features from the roads that intersect the flood 2 m height polygon involves highlighting the entire road segment so that if any portion of the road touches the polygon, the entire road segment is highlighted, which may not be the intention.

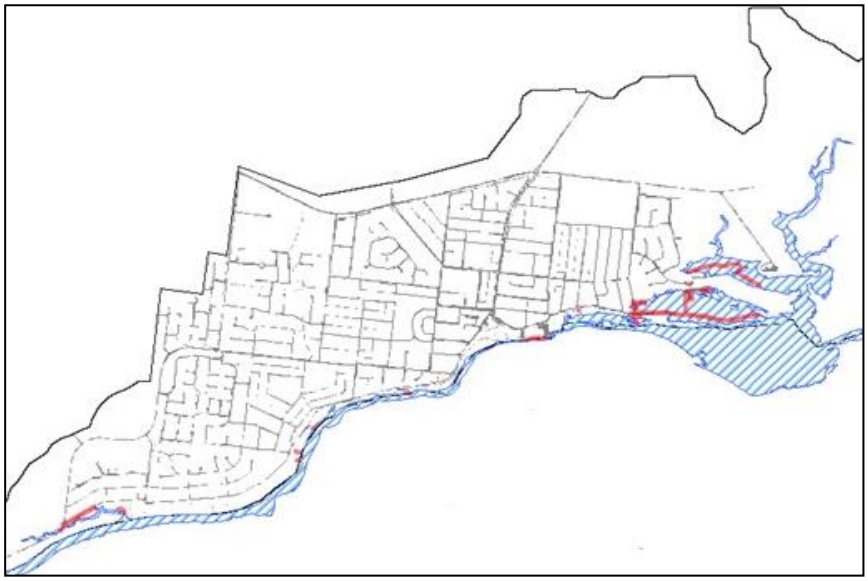


Figure 7-9: Roads at risk from 2 m sea-level rise flooding (highlighted in red)

Therefore, a more appropriate way is to use a geoprocessing method using ArcGIS clip tools to identify only the portions of the roads that fall within the flood polygons. In other

words, the input feature is clipped. Once the clip was executed a separate layer that only identifies those roads that fall within the polygon was created.

To calculate the percentage of road length of the town that falls within the flood prone areas, an attribute for the road layer is required. The column called “shape length” only appears in a geodatabase feature class which automatically appends a shape length or shape area, depending on the geometry, to the attribute table so it can then be updated. This provides the real-time data and the units of the coordinate system in metre by using the statistical tool, “r” the total length of streets that fall within the flood area. In the Inverloch area, the total road shape area is 63.70 hectares (ha). Based on the increase in sea level projected for 2100, the SLR identification of the flood risk to road infrastructure is 1.35 hectares (ha) and 0.86% of roads. The percentage of the town's roads that fall within flood risk that can be calculated by examining roads lengths within the town looking at the sum for all the roads (approximately 1.35 hectares lengths). The area that was in the flood area was divided by the total area of roads, resulting in 0.9% of all roads at risk of flooding in the worst-case scenario. Similarly, 6165 buildings were identified as the total number of buildings in the Inverloch area, and of these, for the 2100 SLR scenario 221 building infrastructure was identified as at-risk i.e. 3.6% buildings will be flooded (Figure 7-10).

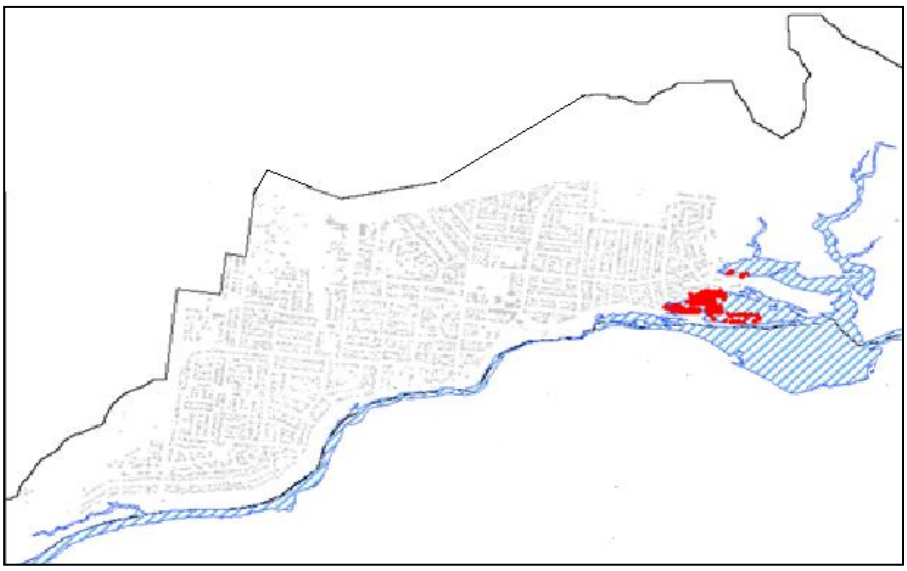


Figure 7-10: Buildings at risk from 2 m SLR flooding (highlighted in red)

This research also identifies infrastructure at risk under different SLR flood scenarios in ArcGIS. Using flood polygons to clip and use that intersect to calculate the total area of each land use summaries.

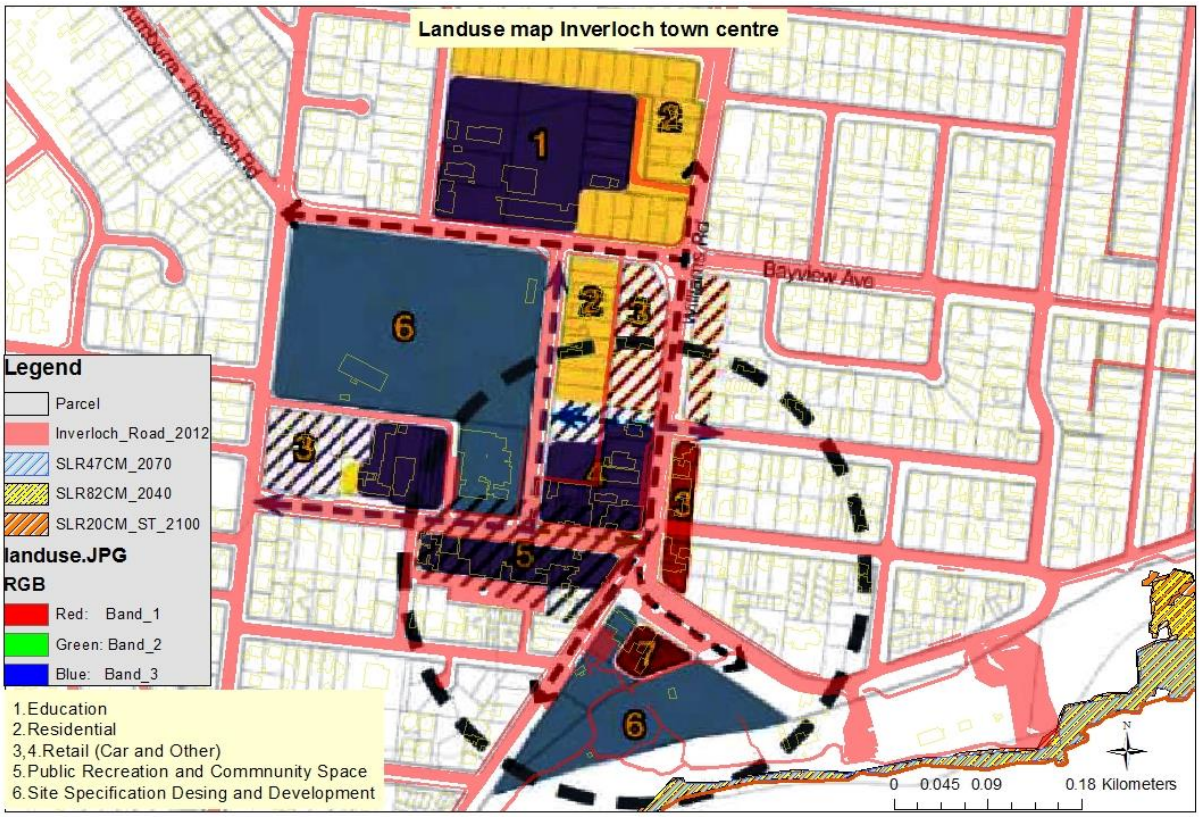


Figure 7-11. Commercial and residential land use at risk of sea-level rise flooding

As illustrated in Figure 7-11, the Inverloch area land use layer identifies all the different kinds of land use within each neighbourhood. This layer is used throughout Australia and can be complicated, depending on the size and the activity that goes on in a neighbourhood. For the land use description field, six separate colours were applied to each category to distinguish the variety. The reason for this is to identify the different types of land use that would be affected by each flood type and identify by number and percentage the proportion and area of each land use that falls within the flood zone. This works in a very similar fashion to that of the roads, by supplying the select location to find land use polygons that intersect with the flood areas. By using the geoprocessing clip tool to make the land use polygon clip from the flood polygons the land use affected by floods in Inverloch is shown.

The clip feature creates each of 2040, 2070 and 2100 flood polygons. The result is an output from the geodatabase that allows distinguishment of these three flood polygon layers from each other, so it is clear which scenario this belongs to. After geoprocessing, the land use layer is produced. Knowing how many records are selected is not adequate, it is important to also know the kinds of land use and the area for each land use type. The land use table provides data on the different categories.

The land use description column also provides statistics, such as the sum of the total area for each land use type that falls within the flood area (see Figure 7-11). Therefore, this research involves a method that distinguishes the types of land use that might be affected by inundation under various SLR scenarios.

The Inverloch town centre contains a range of commercial, retail, community and recreational structures. Near the foreshore reserve, the built form is generally low rise, and the town centre creates a sense of place for residents and visitors. Creating pedestrian links and landscaping in the public realm improves the look and enjoyment of the town centre. There is also the potential for mixed-use retail with housing above, and infill development at the edge of the town centre, with evidence of this form of development emerging in recent years.

The design, setback and massing of this type of housing will require clear guidance to ensure that it sits comfortably within the natural environment and contributes to neighbourhood character in these areas. Opportunities for the expansion of the retail and commercial areas within the town centre and at its edges are evident, through the development of vacant or under-utilised sites, and/or the re-configuration of existing buildings and car parks. Any expansion, however, must consider the risk of inundation. The overarching objective will be to reinforce the town centre and avoid fragmentation of retail into outer-lying parts of the town centre. Inverloch contains a good mix of informal and formal leisure and open spaces. Based on the land use map and the connection

between land use in coastal areas and future flood risk it is obvious that the Inverloch town centre is at risk of flooding, based on SLR predictions for 2100.

7.3.1 Identifying the Population at Risk under Various SLR Flood Scenarios

This section describes the process used to identify the population at risk under various SLR scenarios. It includes an assessment of the consequences of SLR on the population, families and homes in Inverloch. The period from 2016 to 2026, i.e. the short to medium term, is presumably the most exact and helpful expectation of data for quick analysis. It is essential to consider the connection between population and normal family size.

Table 7.2: Inverloch 2016 census. Source: Australian Bureau of Statistics, Census of Population and Housing 2011 and 2016

Inverloch - Pound Creek - Total people (Usual residence)	**2016**			**2011**			**Change**
Population group	**Number**	**%**	**Bass Coast Shire %**	**Number**	**%**	**Bass Coast Shire %**	**2011 to 2016**
Males	2,620	47.9	48.5	2,330	48.1	49.0	+290
Females	2,852	52.1	51.5	2,510	51.9	51.0	+341
Aboriginal and Torres Strait Islander population	51	0.9	0.9	24	0.5	0.7	+28
Australian citizens	4,911	89.8	88.1	4,368	90.2	88.5	+543
Eligible voters (citizens aged 18+)	3,889	71.1	70.1	3,508	72.5	70.1	+381
Population over 15	4,552	83.2	83.7	4,014	82.9	83.0	+539
Employed Population	2,027	95.6	93.6	1,921	97.5	95.3	+106
Overseas visitors (enumerated)	33			19			+14

As we can see from Table 7-3 as the number of households is projected to increase and household size will remain the same, the number of people exposed will increase.

Table 7.3: Forecast of population, households and dwellings, from 2016 to 2036, Source:(Community, 2019).

Inverloch–Pound Creek	**Forecast year**				
Summary	2016	2021	2026	2031	2036
Population	5,525	5,972	6,392	6,887	7,413
Change in population (5yrs)		447	420	495	526
Average annual change		1.57%	1.37%	1.50%	1.48%
Households	2,454	2,654	2,861	3,086	3,312
Average household size	2.21	2.21	2.20	2.20	2.21
Population in non-private dwellings	107	107	107	107	107
Dwellings	4,335	4,671	5,026	5,413	5,803
Dwelling occupancy rate	56.61%	56.82%	56.92%	57.01%	57.07%

The demographic census data that are collected are reported for the nation as well as down to census districts (See Figure 7-12). The census districts are what is relied on to model the affected populations. The easiest way to understand this is to start with a place, in the census that essentially means a town to represent the distribution of the population within the study area then:

a) Map the population data based on Mesh block (MB).
b) Use the highest flood possibility scenario polygons created earlier.
c) Be familiar with the attributes of MB layer.
d) Look at the data column which gives the name of the town or city to which MB belongs (or as the census would say the county subdivision).
e) Display the map based on the properties of the population.

The density varies across the study area. The first step is to isolate the Mesh blocks that belong to an individual neighbourhood and drag the mesh blocks slightly down the boundary of the study area and the flood area and isolate the mesh blocks in a variety of ways. The next step is using the clip tool and considering the census data and the flood layers carefully. Since the data are from two different sources the overlaying accuracy of the data may be unreliable. Selecting by attribute, based on the designated city or town area of the blocks, is the best. This technique reduces the processing time and enables a comparison of the impact on the total population if the population is evenly distributed across the Mesh blocks. Also, there is the assumption that, if a proportion of the area is affected, the same proportion of the population is affected. Finally, geoprocessing tools were used to clip the census block layer using the flood polygons.

The next step involves identifying how many neighbours or a census block with a unit area of one is flooded - for example, one hectare and that the population is that of that census block. An assumption is made that flooding occurs in the entire area and the entire population has been affected by flooding. If only a portion of the census block is flooded, the assumption is made that the entire population is affected. However, it is important to consider the proportion of the population affected. To identify the number of buildings affected, we need to assume that the flooding affects about 3.5 per cent of the buildings.

For the 2100 flood model projection, it was indented that the building infrastructure at risk is 221 (out of a total number of buildings of 6165). The average people per household is 2.2 (see Figure 7-12). Therefore, if we multiply 225 (See the population figures in Table 7.3), it is possible to estimate that 495 people will be affected (if the population is evenly distributed). So, this is the current scenario model technique. The average annual change by 2036 will be 1.48% see Table 7.3.

7.4 GIS-Based BCSC Scenario Modelling

Section 7.3 already discuss total road area in Inverloch is 63.70 Hectares (ha). By 2100 SLR Identifying Road Infrastructure at Risk will be 1.35 Hectares (ha) and 0.86% of roads

will be flooded. In 2040, 0.95 sq km 8.75%. In 2070, 1.09 sq km, 10.03% and in 2100 1.16 sq. km, 10.67%.

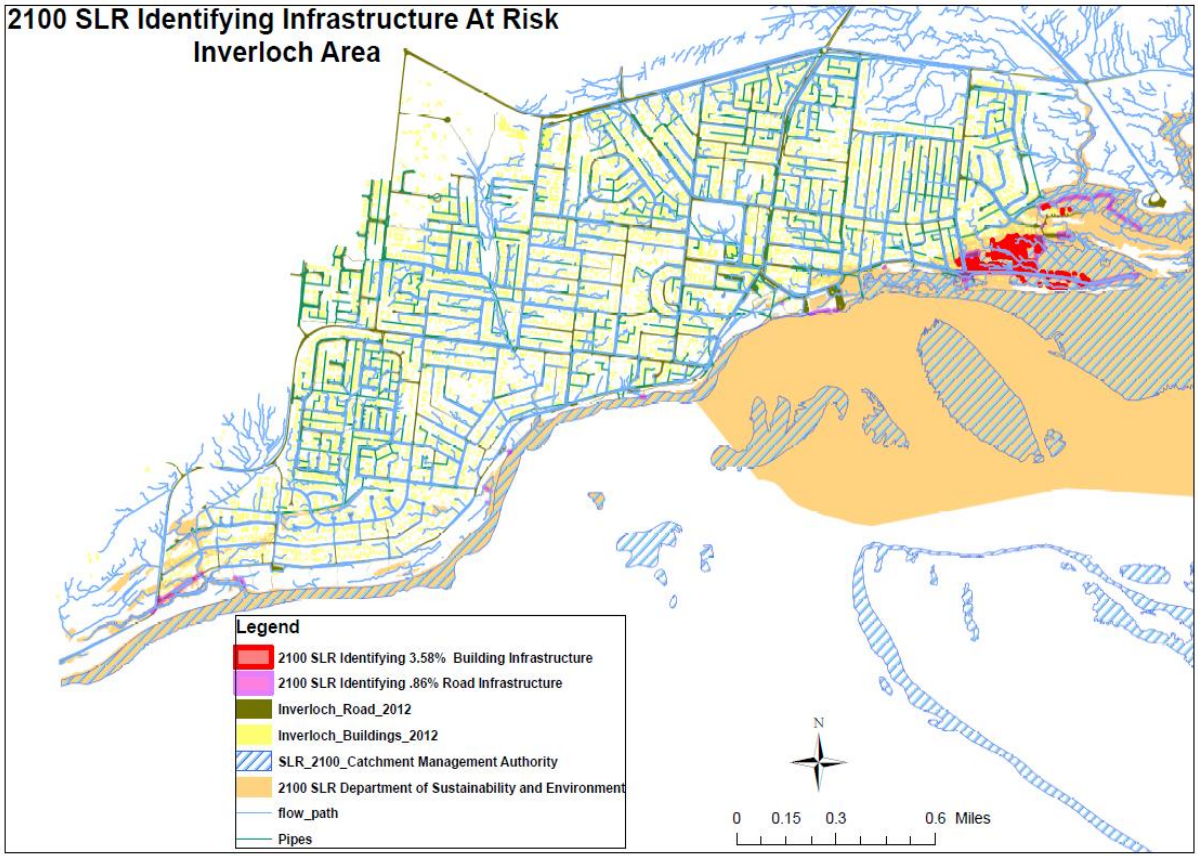


Figure 7-12: Inverloch climate-adapted settlement in 2100 SLR identifying assets at Risk

In Figure 7-12 the roads are shown as a dark olive-green shade, with the most exposed roads shown as dark pink. The buildings are shaded yellow, with the most exposed shaded as dark red. When overlayed on the buildings' footprints buildings were identified as being highly vulnerable as those in the highest level (red colour here) and the lowest vulnerability in yellow and it is evident that most buildings are exposed. The most highly exposed roads (143 kilometres) and buildings (6100) were in the Inverloch holiday park area, with 65 buildings were exposed in the Screw Creek area. These are most evident at the eastern end of the image.

To determine the population affected, residential buildings were multiplied by 2.2 (assumed average household size in Victoria), in order to predict the population exposed.

It is evident that most of the population exposed were in Inverloch followed by the Inverloch near to the holiday Park and fewest at Screw Creek. The 2018 population forecast for Inverloch–Pound Creek was 5,741, which is forecast to grow to 7,413 by 2036 (see Table 7.3).

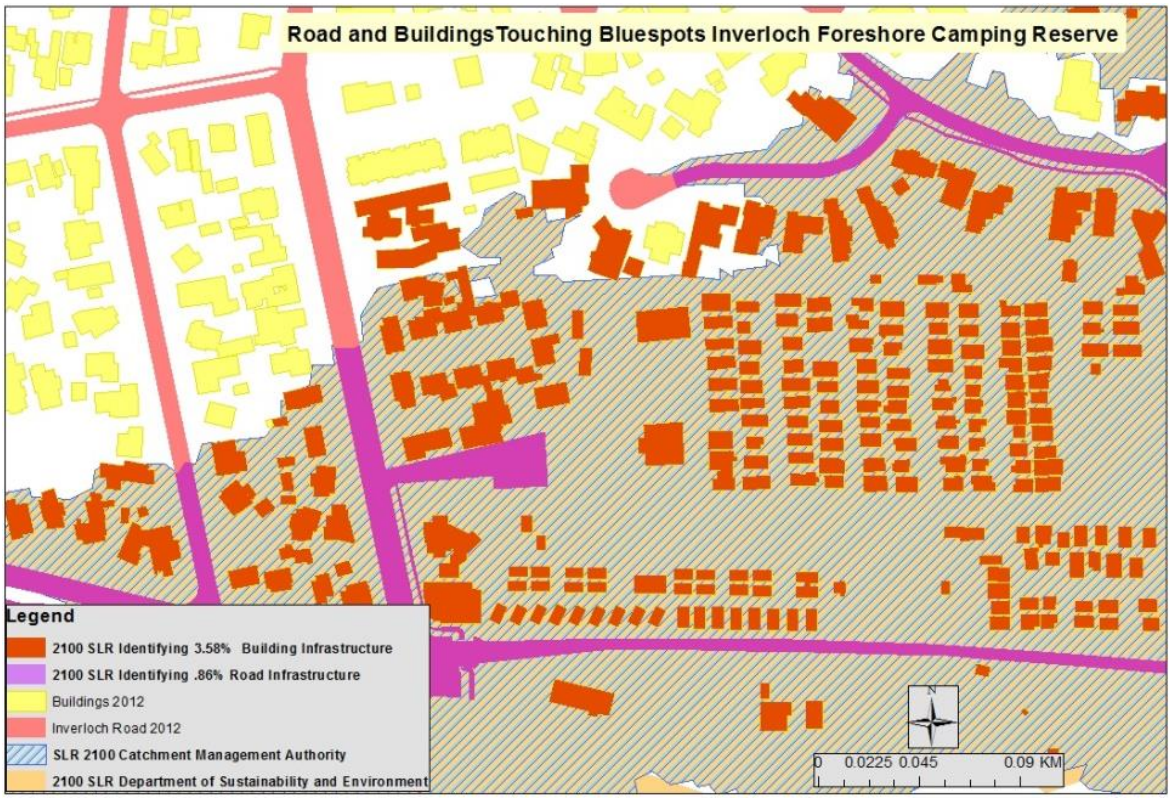


Figure 7-13: Inverloch Foreshore Camping Reserve climate-adapted settlement in 2100 SLR Identifying Roads and Building Infrastructure at Risk.

Issues to consider in connection to the future of the built environment of Inverloch include:

- Is a traditional gravity sewer framework the most appropriate system for Inverloch in a climate change situation? This could expand groundwater and lead to intermittent flooding of low ground. Alternatives could a STEP (utilizing existing septic tanks) in the medium term, trialled by a progressively low weight or vacuum framework later.
- How to solve existing problems with Inverloch stormwater disposal/sewer backup. climate change is likely to exacerbate these factors, meaning the impact of extreme storm events will be exacerbated.

- The predicted impact of SLR on flooding in the township, as well as degradation of coastal landscapes.

While floods will occur in the future from sea storms (Figure 7-12), improved information creates an opportunity to address these climate change adaptation issues influencing the settlements. As discussed in Chapter 8, there are some coastal areas of Inverloch that are particularly vulnerable to flood risk. These include the centre of the town near the caravan park (open space, barbeque area, and marine national park) which are vulnerable to an increased risk of flooding, especially when combined with riverine flooding. For Inverloch, the major inundation risk is a severance of access due to water travelling overland from Shallow Inlet and cutting roads leading into the settlement.

The maps provided in this Chapter don't illustrate the depth of the water over the street, so local studies would be expected to better understand the degree of flooding at specific points. An important impact for Inverloch from rising sea levels is the increase in erosion of the beach and dune systems. Inverloch is currently drained by three creeks, none of which has a large basin. The increase in run-off due to impervious surfaces related to urban development and the increase in rainfall intensity has not been offset by a corresponding increase in capacity in the inlets and in the underground drainage system.

As noted above, there is a high risk of flooding in the town business and retail centre and in locations close to river inlets. This could increment with climate change because of the likelihood of more frequent and intense precipitation events and SLR, which will impact drainage.

Figure 7-14: Inverloch boat ramp (source: Google Maps)

In the event of a storm event (currently) of 1 in 10 years, a storm surge / rapid rise / SLR of 1.85 m will affect most of Inverloch boat ramp, see Figure 7-14. A 1 in 10-year rainstorm event would cause flooding of a large portion of the city's shoreline east of the boat ramp with ocean water impacting the protective rock face near the Inverloch Bowling Club (Monash, 2012).

The Anderson's Inlet's sand dunes and sandbanks may be inundated completely. At a storm surge of 1.85 m, parklands in front of the main esplanade can be flooded as well. But a spike of 1.85 m does not represent a noteworthy risk to the properties of Inverloch. It is normal that a storm occasion from a 1 in 100 years will make the ocean ascend to 2.35 m in Inverloch (Figure 7-15). At this amount of SLR, flooding becomes a major concern for the township, with numerous properties and streets undermined by rising water levels. To the east of the boat ramp, almost the entire beach would be flooded, and the water would inundate the main road and the central city. Assuming a 1 to multi-year flood, it is predicted that 75 properties will be inundated by the flood. Moreover, the retreat being constructed west of Screw Creek is at risk of being totally submerged. When flood in the severity of a

storm in the future (Figure 7-15), it is likely that this is the time to address climate issues. A severe storm event for Inverloch is discussed in detail in Chapter 6. In Inverloch, there are some areas in the town centre near the caravan park that are exposed to increased flood risk from the sea over the medium term, particularly when combined with catchment-based flooding.

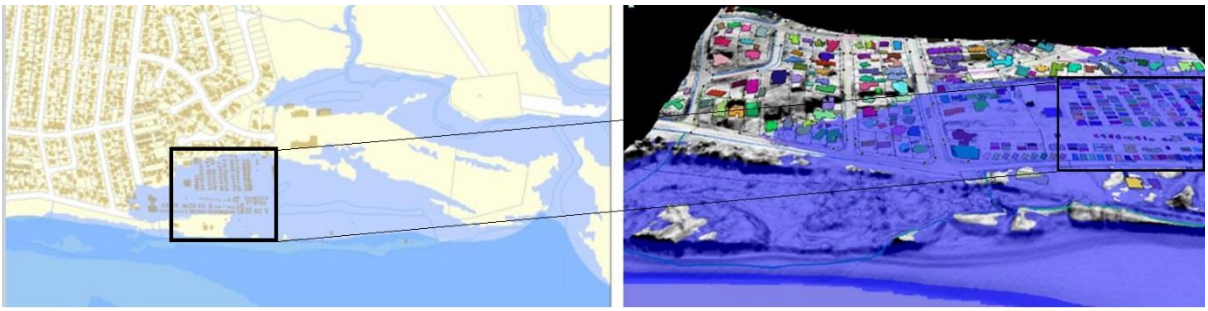


Figure 7-15: Coastal flood datasets: 2040 storm (Stanley et al., 2013).

This research has identified vulnerable houses, as well as the impacts on assets, infrastructure, and water bodies. This research identifies vulnerable assets such as roads, bridges, drainage, buildings, boat ramps, jetties and infrastructure, as well as houses and surf clubs. It identifies where flood will occur due to SLR and storm movement, together with stormwater drainage catchments and overland flow paths to see what amount of water flows where.

7.5 Results and Discussion

The research presented in Chapter 7 assists with future land use planning decisions by modelling the potential flood risk from SLR on coastal infrastructure. Future planning controls such as the LSIO may prevent development in areas “at-risk” of inundation, for example allowing only removable buildings to be erected on low lying areas.

This modelling helps inform the location of Land Subject to Inundation Overlay (LSIO) that flag properties and infrastructure at risk from future coastal and river flooding. The BCSC water catchment areas are governed by West Gippsland Catchment Authority and

Melbourne Water. These authorities provide data on the proposed water level rises. To support these agencies in implementing the state planning policy, there is a need for (i) improved planning for SLR, (ii) ensuring new development takes into account climate change impacts and (Hine et al., 2017) ensuring that new development is not allowed on land subject to coastal flooding.

Figure 7-16: 2016: Current mean high watermark at Pioneer Bay, 2050: One mean high watermark at Pioneer Bay, 2100: Two meters mean high watermark at Pioneer Bay (BCSC,2018).

The mapping work also assists in future land use planning decisions (see figure 7-16). To support planning decisions, the research presented in Chapter 7 used tools for sharing data in Google Earth using the open-source MyGeodata Converter tool to share information with the LGA planning department (see Figure 7-17).

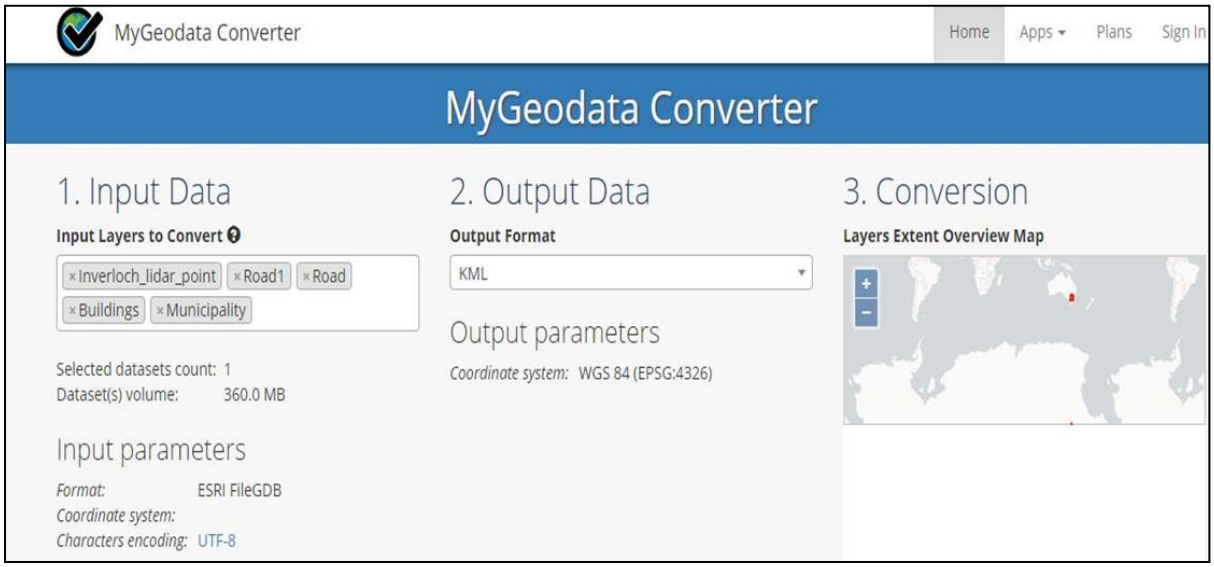


Figure 7-17: MyGeodata Converter

Figure 7-18 shows an overview of the data comparison analysis - DELWP, CMA and Cloudburst. Comparison can be easily done with Google Earth because different organization use a different format of GIS data.

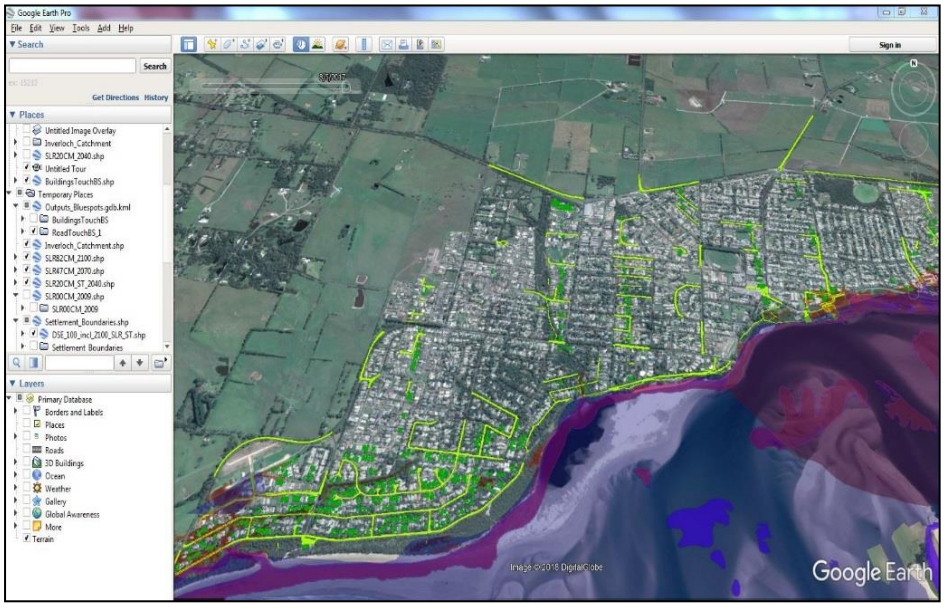


Figure 7-18: An overview of the data comparison analysis, DELWP, CMA and Cloudburst

Decision-makers from local government and other stakeholders can use the map provided in Figure 7-18.

The BCSC ‘Natural Environment Strategy 2016 to 2026’ (NES) (BCSC, 2014), argued for creating sustainable places in responses to climate change. In view of this examination, local governments assemble, manage and maintain government assets. These actions are long term and face risks due to climate change. Adapting to climate change is important to ensure that the effects of climate change are limited. This is essential for protecting assets from (i) storm surges and severe climate events, (ii) increased frequency and intensity of floods and droughts, and (Hine et al., 2017) increased risk of heatwaves and bush fires.

The Inverloch area has mainstreamed climate change into asset management. This research model provides information on the risk of flood to public and private development assets (e.g. new housing, long-term road management, park asset, coastal infrastructure, drainage). Council also currently incorporates Climate Change Adaptation into Asset Management, through:

- Improvement in WSUD functionality to control the quantity and quality of water runoff.
- Retention of stormwater after storms to reduce erosion and sedimentation downstream.
- The Asset Management Plan and Strategy 2018 which identifies climate change as a risk and recommends the use of Environmentally Sustainable Design (ESD) values in the planning and design of operational and capital works for the Municipality.

The results in this Chapter highlight climate impacts on infrastructure, developing more resilient technologies and, above all, developing a better understanding to quantify the impact or benefits of climate adaptation strategies. The main conclusion of this research is that asset management undertaken according to best practices is one of the most significant climate adaptation strategies.

7.6 Chapter Summary

The results presented in this Chapter show the impact of SLR during a storm if the elevation levels represented by the DEM are stable. The model may also indicate which coastal areas are in danger of being flooded by a slow increase in sea level due to climate change. However, in very dynamic coastal areas where erosion or accumulation rates are high, the landscape is subject to changes in elevation levels causing detailed predictions very unreliable, especially if the SLR is pending for many years.

The hydrological models to identify the dams, which is useful when making decisions about the protection of shorelines. This information may also be useful when considering temporary emergency protection of areas at risk of getting flooded by deploying mobile flood barriers. The research also contributes to the literature on hazard risk by creating an infrastructure risk model in Inverloch. Resilience can be increased, and vulnerability reduced, when structural mitigation responses are implemented to mitigate future multi-hazard coastal inundation in low lying areas. Local government can use this GIS-based infrastructure risk model to inform residents of their exposure and implement and restructure land use planning to reduce vulnerability to key assets.

Chapter 7 described how a spatial decision support system helps to identify infrastructure at risk (such as buildings and roads) from SLR flooding. This research responds to intermediate research question 5 (section 1.3) - How does a spatial decision support system help to identify infrastructure at risk from SLR flooding? To address this research question, research was undertaken based on asset management stakeholder's knowledge as part of the research (including from road, building, and land use control authorities). These authorities have indicated their organisations have either started or will shortly commence risk assessment processes to better understand their risks to future climate change for existing assets and in the context of proposed expansion. Research tools provide a practical approach to addressing current and future climate risk on coastal infrastructure assets and operations. While a broad range of potential resilience and adaptation measures have been identified, it should be noted that climate risk management is a 'long game' issue and there is no single approach or tool that can effectively eliminate climate risk in the short-term.

The next Chapter begins with a summary of the research results, responds to the research questions, and afterwards looks at certain directions for future research that have been raised amid this hypothesis.

Chapter 8

8 Discussion and conclusions

8.1 Introduction

The previous Chapters 4, 5, 6, and 7 presented a method for mapping overland flows and legal points of discharge, delineating watershed, modelling hydrologic connectivity of inland areas with SLR, and assessing flood risk to buildings and infrastructure associated with different SLR scenarios.

Local government areas (LGAs) with coastal boundaries are required to develop strategies to manage their exposure and response to flood risk. To inform the content of these plans a method is required for mapping the overland flow and determining the legal points of discharge, flood basins and their hydrological connectivity. The main purpose of this research is to facilitate the analysis of the risks associated with coastal flooding using GIS-based hydrological modelling. This concluding Chapter aims at answering the research questions posed in Chapter 1 and combining these responses to draw conclusions and make recommendations related to each of the research objectives. It examines the results achieved during this research, emphasizes the significance of the research work, reflects on the problems of original research and suggests directions for future research efforts.

Three SLR scenarios were used to illustrate how flood risk varies with climate change and SLR projections in terms of the extent of flood risk to buildings and other coastal infrastructure. The model developed was used within the Bass Coast Shire Council (BCSC). It was found that the way the variables interacted required that traditional model inputs be refined to meet the needs of BCSC, as presented in earlier Chapters.

This Chapter begins with a discussion of how the research responds to the intermediate research questions and then analyses some directions for future research plans that have been raised during this thesis.

8.2 Research Related to the Aims, Questions and Objectives

As previously discussed in Chapter 1, the central aim of this thesis is as follows:

Develop GIS-based hydrological tools to support local government decision-making with an emphasis on climate change in a coastal flood risk management framework.

Research findings presented in Chapters 6 and 7 refined current approaches to risk assessment methodology, enhancing approaches that identify the impacts of a cloudburst including the houses and infrastructure at risk from flood damage. This research is relevant to low-lying coastal areas in Victoria in addressing the impact of storms and SLR.

The research presented has demonstrated that observed water volume increases in rivers, creeks, closed embankments, low lying land and swamps are caused by an interaction of many variables. Some of these variables are easily quantifiable and of these, the following variables were shown to affect the extent of flooding in an area:

- The intensity and amount of rainfall.
- Absorption and runoff of water over the surface and substratum.
- Variation in the tides.
- Wind direction and intensity.
- The type of catchment.
- Previous precipitation history.

The literature review illustrates that GIS is frequently utilised in the processing of large datasets and modelling, analysis, simulation and visualisation of real-world relationships, patterns and processes (Pham et al., 2017). It also reveals that GIS-based data integration and GIS-embedded hydrological modelling can be used for coastal flood management. A key finding of this research is that the current tools available to flood risk managers have limitations in the level of accuracy that affects the quality of flood predictions.

The research has determined that the integration of LiDAR data into GIS-embedded hydrological modelling improved the accuracy of the outputs and helped the development of a spatial decision support system (SDSS) that can increase the confidence of decision-makers in the outputs. This technology has the ability to support risk assessment, adaptation planning and decision making (Alshuwaikhat et al., 2017). The GIS-embedded hydrological model developed as a result of this research derives more accurate predictions. This will help LG planners identify areas that are highly impacted by floods caused by either sudden or long-term SLR. In this context, the research objectives will now be reviewed and discussed.

8.3 Responses to Research Questions

To achieve the research aim, this research included the following intermediate research questions:

1. What is the current status in the integration of GIS with hydrological modelling and multi-source spatial data systems?
2. What is the current policy-to-practice gap in coastal flood-related spatial information management?
3. How can an GIS-embedded hydrological model be used to improve the existing GIS database?
4. How can the current process for drainage analysis be improved?
5. How does a spatial decision support system help to identify infrastructure at risk from SLR flooding?

8.3.1 What is the current status in the integration of GIS with hydrological modelling and multi-source spatial data systems?

The research in Chapter 4 described why hydrological models are important tools for the analysis of water resources, and the importance of integrating these models with GIS and spatial data for deriving accurate results. GIS models were developed to include LiDAR data on topography and integrate accurate spatial data with appropriate detail about the infrastructure. By including these parameters in the hydrological models and applying the

models to the case study area, the direction and movement of the overland flow in coastal urban settlements can be modelled and simulated.

The study revealed that it is possible to demarcate an urban overland flow path and extract detailed information about each catchment through hydrological modelling. The specific influence of both pipe-based drainage networks and minor drainage networks on overland flows was also explored. The study found that regardless of the influence of artificial structures, the topography of the natural surface is the main determinant of the behaviour of overland flows.

Results presented in Chapter 4 demonstrate how practitioners can use hydrological analysis for the development of distributed hydrological parameters in a quicker, easier and more accurate manner than traditional methods. The distributed flow model described in Chapter 4 can be regarded as the most critical one to be utilised because it can identify overland flow paths along roads and canals and identify open spaces that can store excess water from flood events. By modelling the LiDAR-derived legal point of discharge (LPD) in conjunction with these data, the BCSC will be able to better manage the risk of coastal flooding. It was also demonstrated that it is fundamental that multi-source spatial data be included in any flood-relevant GIS database. Specific attention should be paid to the accuracy of the source delete data on surface topography required to facilitate high-quality flood model outputs. To accurately model and simulate the true behaviour of overland flow, it is recommended that GIS practitioners use the most up-to-date LiDAR data available in their hydrological models.

8.3.2 What is the current policy-to-practice gap in coastal flood-related spatial information management?

Understanding of the complexity of floods and the flood risk need to be understood. managed and included in the current policies on flood risk management. The techniques used to address knowledge gaps can vary from catchment to catchment. More sophisticated techniques should be applied in areas with high flood risk exposure or where floods exhibit more complex behaviour. Simple techniques can be used in areas where flood behaviour

is more predictable, or development is less concentrated. The expectation is that knowledge on and management of flood risk will improve over time, so will the capacity of and resources available to flood managers. The literature review identified that efforts to better understand and manage risk are likely to be focused on areas where flood problems are the most complex. Improved knowledge of risk is needed, particularly where the existing exposure is high or where exposure due to future growth is likely to be high.

Coastal floods are natural events that repeatedly impact on the coastal landscape and cause stressful impact on people and significant damage to properties and the environment. In the context of climate change, the integration of spatial planning with flood risk management has gained importance as an approach to mitigating the risks of coastal flooding. Is the main gap the spatial data, or the integration of GIS and hydrology, or both? The main gap the high-quality spatial data, integration of GIS and hydrology. Similarly, minimal research has been conducted on the role of integration of spatial data and GIS with hydrological modelling for the purpose of climate change adaptation.

In Chapter 2, this thesis explored the governance structures, challenges and opportunities that flood administrators and emergency workers experience in managing coastal flood risk. Much has been accomplished since the publication of the fourth Victorian Coastal Strategy (2014) which provided the Victorian government with a high-level policy framework for climate change planning along the coast. A series of policy documents provided opportunities for various government departments and authorities, local councils, developers and individuals to respond positively to flood risk mitigation challenges. The opportunities and challenges are described in Chapter 2 of this thesis. Chapters 4, 5, 6 and 7 expanded on this and examined answers to the existing challenges, including:

- How to enable coastal area communities to develop in order to address the current risk and future hazards related to flood.
- How the different coastal climate risk management tool should be considered (SLR, tidal effects, storms and erosion).
- How to improve methods for flood hazard mapping

- How to benefit from technological improvements and forecast accuracy for monitoring and reviewing physical changes.

Spatial information has been provided to enable the evaluation of the risks imposed by coastal flooding, and as a result, coastal flood planning in BCSC is now better organized than ever, although there are still concerns about the quality of data and information available. Spatial data quality can be categorized into data completeness, data precision, data accuracy and data consistency. Uncertainty about which processes should be applied and under what circumstances, the strategies for flooding in its local planning policy framework will allow for improvements over time. Continued significant effort from all stakeholders, including government, businesses, communities and individuals, will be needed to ensure that risks associated with coastal flooding and SLR are managed effectively.

This study proposes that a hydrological model integrated with GIS can support spatial planning and flood risk management processes. This is achieved through modelling the impact of different planning and management scenarios (including changes to land use) on coastal flood risk. Furthermore, the SDSS developed in this research allows for the accuracy of flood hazard maps to be assessed in preparation for flood disasters, evaluation of development scenarios and for decision-makers to combine coastal flood management with coastal planning.

To address the current policy-to-practice gap in coastal flood-related spatial information management, the use of the following policies, tools and data are recommended:

- SDSS based on coastal flood risk assessment to inform future socio-economic planning by coastal authorities.
- Existing policies and decision-making processes of a Victoria coastal planning agency and flood risk management systems (AMS).
- Spatial and hydrological data models developed to generate the spatial tools required by the coastal council to enable a decision-making. The geospatial data process of incorporating the influence of a coastal drainage system into typical

hydrological models integrated into GIS, such as Arc Hydro, SAGA, ArcSWAT, to improve the extraction of a network of river paths in a coastal basin.

- A visualization tool that helps SDSS greatly improves the coastal area.
- Flood risk model development to determine flood-prone areas in a downpour.

Identifying which department of a coastal council will be most important for modelling SLR and infrastructure risk assessment.

8.3.3 How can a GIS-embedded hydrological model be used to improve the existing GIS database?

Approval of coastal land development applications in Victoria is subject to an assessment of how the proposed development addresses exposure to flood risk. The purpose of Chapter 4 is to outline how hydrological models created from ArcGIS extension Arc Hydro and SAGA can help identify overland flow paths, drainage subgroups, legal points of discharge (LPD), and permeable and impermeable surfaces. The research found that the quality of drainage data needs to be improved to obtain an accurate modelling of the impact of a flood on BCSC coastal drainage infrastructure.

Chapter 4 also describes how LiDAR data has improved the quality of modelling and understanding of how hydrological parameters affect coastal flooding systems (Zomorrodianc, 2012). Seawater can cause flooding over the mainland through several different flow paths. Traditionally, defining basins and flow paths requires a lot of time and research. Typically, drainage areas, overland flow paths, LPD and permeable surfaces were identified using topographic maps, while drainage and terrestrial flow directions were calculated by analysing a DEM or by visually inspecting the slopes of the terrain on-site (Monreal et al., 2018). Within a GIS, hydrological data makes it possible to integrate different landscape and environmental data, including climate, land use and topographical features. The combination of GIS technology, hydrological modelling and spatial data documented in Chapter 4 offers enormous benefits to coastal flooding modellers and engineers. This Chapter presented two different methods for determining basins and flow paths using automated GIS functions, and concluded that programmed methods with

physical delineation and the Thiessen polygon method in sewage basins were the most accurate overland flow delineation tools.

Chapter 5 described a watershed model - the soil and water assessment tool (Grover, 1999) - that uses hydrological response units (HRUs) to describe spatial heterogeneity in land cover and soil types within a watershed. The model evaluates the relevant hydrological components such as surface runoff, groundwater flow, and evapotranspiration and soil moisture change, for each HRU. This Chapter also discusses the usefulness of flood simulations in decision making and flood control planning.

Chapter 5 demonstrated that two-dimensional (2D) visualizations are not enough to present the real scene and therefore cannot make a full representation of the situation. In this research, SWAT was used to generate 3D simulation model outputs for the individual sub-basins of the Ayr River basin. This output identified seven sub-basin parameters in the main basin. The watershed included sub-basin parameters in which each sub-basin has the distinctive features of the HRU.

This research finding demonstrates how 3D simulation can be relied upon to trigger flood management activities such as planning, mitigation, alert and rapid response. However, for generate, engineers and hydrological modellers to improve the accuracy of their predictions, development of complete coastal flood GIS databases using high-quality climatic, topographical, soil, land use and land cover, as well as buildings and infrastructure data sets with appropriate scale and enough spatial details are required. Appropriate data and GIS-embedded hydrological models are used to develop new information products to support coastal flood-risk planning. The information products developed in this research meet the research objectives 1 and 2.

8.3.4 How can the current process for drainage analysis be improved?

Chapter 7 provided detailed information on coastal flooding that is important to understanding the population dynamics that are affected by storm surges and coastal

flooding. To understand these natural flood risks, DEMs are often used to model floods in coastal areas. A single-value surface method is sometimes used to inundate areas in DEM that are below a reference plane with a constant and specified elevation value. However, such an approach does not take into consideration hydrological connectivity between elevation grid cells resulting in inland areas that should be hydrologically connected to the sea. Using a LiDAR elevation surface, it was discovered that the inland areas that should discharge to the sea were, in fact, hydrologically disconnected and that the simple raising of the overall water level to replicate what happens in coastal flood events impacts the accuracy of these flood model predictions. Specifically, it was determined that this approach is problematic because it does not consider the hydrological connectivity between the cells of the elevation grid.

To address this problem, a LiDAR-based elevation surface was developed which made the identification of the hydrologically disconnected inland areas possible so that they could be considered as part of coastal flooding models prior to any flood analysis. The process of identifying hydrologic connectivity with hydrologic enforcement is not new. However, this research is innovative because it was found that when hydrologically-enforced LiDAR elevation surfaces were applied, current drainage analysis processes were refined enough to accommodate climate change-oriented scenario-based modelling.

A current challenge facing GIS practitioners is to determine climate-related flood risk in areas that are much higher in elevation than sea level. In Chapter 7 the focus on coastal watershed patterns and their risks allowed the full impact of coastal disasters associated with climate change to be investigated. BCSC Inverloch coast, which suffers from erosion, was selected as a demonstration area for vulnerability analysis based on SLR predictions, wave augmentation, superstructure and coastal flooding predictions from 2030 to 2100. Hydrological connectivity is achieved by making correct hydrological decisions (Krysanova and White), to achieve a correct simulation of the overland flow in a LiDAR based model (Poppenga et al., 2014). Elevated topographical features (i.e. bridges/roads) were found to contribute to downstream overland flows when exposed to simulated high-volume downpours.

The IPCC predictions (Church et al., 2013) indicate that by 2030 the sea level on the Inverloch coast of BCSC will increase an average of 0.2 cm and, by 2100, will be increased by 1.1 meters. The analysis indicates that the municipality of Inverloch is at high risk and does not have the infrastructure required to resist these impacts. This assessment provides important information for the creation of a climate adaptation policy for Inverloch in the BCSC, specifically in the part of the catchment that is connected to the coast but does not have adequate flood measurement data to allow planners to predict flood impacts. For this reason, it was not possible to set a threshold for the classification of the Blue Spot Model (BSM) which identified and assessed flood-prone buildings and roads. This BSM applies a 1D-1D hydrodynamic model of surface reservoirs and depressions (Hansson et al., 2010). The more complex hazard evaluation can be performed with the use of a 1D/2D coupled model, which can be applied in coastal area. Here, a spatially distributed hydrodynamic model is applied for the sewage system in 1D and on the terrain in 2D.

To overcome this limitation to the BSM to delineate areas where the infrastructure was at risk in different SLR flood scenarios. The SDSS identified that storms and heavy rains would result in heavier flooding in lower regions of the basin and that these would be amplified by SLR. A field check verified that the map generated by the model output correctly identified areas that are currently threatened by coastal flooding in real-life.

8.3.5 How does a spatial decision support system help to identify infrastructure at risk from SLR flooding?

The urban coastal landscape is never uniform in height, it is scattered with sinks or depressions that come in all shapes and sizes. To the naked-eye, residential areas, farmland and parks appear level in dry conditions but the location of depressions become apparent when enough rain falls, the soil reaches saturation point and the drainage cannot remove excess water. Roads, buildings and other types of assets such as barbecues, playgrounds and sports fields are also vulnerable. In Chapter 6 these sinks, buildings, roads and assets that are prone to flood risk are identified using the DEM dataset with BSM models. The

main objective of BSM research is to support LGAs that use elevation data to find the locations of flood-prone blue spots so they can prepare their communities for the impacts of a projected extreme rain event.

Flood analysis is of fundamental importance to federal, state, local and educational institutions. Chapter 7 illustrates that current and future flood risk can be identified by combining different flood refinement scenarios in ArcGIS with LiDAR data enhanced hydrological modelling. The results presented in Chapter 7 demonstrate how spatial analysis can be used to accurately identify natural environments and man-made infrastructure likely to be exposed to flood risk as a result of SLR. In Chapter 7, the LiDAR-derived flood polygons were used to identify where infrastructure was at risk. Local government asset data was used to determine the monetary value of properties, roads, and other infrastructure to prioritise the protection of high-value infrastructure that was at risk.

The aim of this Chapter was to develop a method that would improve hydrodynamic flood models using high-resolution LiDAR-derived elevation data and to consider the hydrological connectivity of the internal areas of a catchment with outfall points in the context of SLR. This information is necessary for the monitoring and management of floods in sensitive coastal regions because, in the context of climate-related events, homes and businesses may be directly impacted by storm waves, sea-level rise and floods. Utilisations of these data are also critical for the institutions to accurately predict the ecological impacts of the direct and indirect effect of SLR on coastal areas subject to flooding. These topics are discussed in response to research objective 4 and section 1.2.2.

8.4 Originality of the GIS embedded hydrological model

The integration of the spatial data developed has improved the typical hydrological model integrated into GIS. Archydro tools, to extract overland flow paths and LPD.

The present flood models were developed to predict the coastal areas to be potentially flooded during a storm, if the coastal landscape is represented by a digital elevation model that will keep its steady-state during the event. Results in Chapters 6 and 7 are generated with different flood tools developed for coastal areas assess the risk of damage to infrastructure. Very limited research has been done in modelling the possible outcomes of potential flooding. The research described here is unique and provides the following outputs to assist with flood risk management in coastal zones:

- Locate affected buildings and roads.
- Allow for adding a dam represented by a digitized polyline with a constant level defined by the maximum predicted flood level.
- Scenarios based coastal flood risk model with critical infrastructure.
- Suggest how other parts of the world can predict climate change.

The municipal engineers can compare the consequences of different hydrological models based on different analysis results. Future SLR, floods, precipitation, and infrastructure risk can be factored in for their decisions on the chance of each. The municipal engineers of the local government of the coastal areas can ensure new land development is less exposed to flood. This may also be useful for other coastal local government areas in Victoria have to make decisions based on the risk of a future SLR. Given the significant future costs that could be avoided with cost-effective design changes today, it would be wise for all drainage studies in coastal areas to assess the implications of climate change and SLR scenarios in the future.

8.5 Suggestions for Further Research

8.5.1 Limitations of this research

The limitations identified in this research involve the following issues:

- Recent high-resolution digital elevation models (DEMs) are not available for study area. The latest data available is 2009 DEM data, which means that any housing and development since 2009 is not captured and flood risk hazard mapping is

therefore based on the conditions in 2009. However, the DSS and model developed are still valid and could be applied if new data became available.

- Any spatial applications in the hydrological world are dependent on the accuracy of topographical surface data. this research showed that the LiDAR vertical accuracy was around 0.5m which will produce some very unlikely and highly imprecise bluespots by volume. As a result, in Figure 6-5 and Figure 6-6 some vertical stripes are evident in the results from the BSM, which highlight potential errors in the LiDAR data accuracy.

- The underestimation and overestimation of rainfall during extreme events is typical of the numerous challenges that Hydrological models and simulation models face. They have difficulty capturing extreme events in the system, but also could be due to errors in measuring flow.

- There is no single technology that can measure both terrain heights and water depths to a suitable level of accuracy and density for applications such as storm surge modelling and coastal inundation research. Topographic LiDAR cannot penetrate water to yield bathymetric results. The shoreline is commonly defined as the boundary between land and sea. Because of coastal climate changes and human interventions, the shoreline is constantly changing by erosion and accretion, and BCSC also face this challenge in mapping coastal erosion. Therefore, the water depth, coastal monitoring and shoreline change method needs to quantitatively analyse the shoreline locations and differences in both the past and present using bathymetric LiDAR. In this research airborne bathymetry, LiDAR data is limited for the study area, and therefore the shoreline erosion analysis was not possible.

- Another limitation due to the lack of bathymetric data is that this research was not able to develop topobathy DEM for a specific application (such as shoreline delineation, coastal flood zone mapping, wave modelling, coastal engineering, habitat restoration, and modelling of storm surge, inundation, or tsunami). A topobathy digital elevation model (DEM) is a single surface combining the land elevation (LiDAR) with the seafloor surface(bathymetric).

There has been much research on climate change, however more is needed on the threat of SLR along the coastal zones and to better understand climate models and ways to assess and tackle uncertainty. Within the BCSC, there are specific actions that can be undertaken on a local scale to progress our preparation for climate change. Very limited research has been conducted studying the impacts of flooding on flora and fauna in this area.

Furthermore, there appears to be a lack of research into the short- and long-term environmental impacts of floods in key sectors such as:

- Continuing to develop climate change models to better data assess and address continuing uncertainty.
- Improving local knowledge of coastal authorities to better recognize areas at risk of erosion.
- Improving and obtaining topographic data to understand the extent of flood and loss risks for populations along the coast.
- Determining the degree of flood arising from coastal subsidence along the Gippsland coast and remodelling using detailed coastal DEM based on LiDAR data.
- LGA action to administer risk planning and management tools into decision-making outlines.
- Preparing adaptive management by local stakeholders to find appropriate actions to address threats.

8.5.2 **Future research**

Future research needs an integration of techniques when generating a topobathy surface topography (land elevation) using LiDAR, and bathymetry of the seafloor. Topography LiDAR is generally collected for land-based applications such as hydrology and habitat mapping, and bathymetry is collected for applications that are relevant to the level of the water. The generation of a topobathy surface is complex as it involves combining these data sets using datum conversion and integration techniques to minimize error in high-resolution DEMs. However, the new innovative Topobathymetric Elevation Models (TBDEMs) from multiple topographic data sources with adjacent intertidal topobathymetric and offshore bathymetric sources can be used to generate more accurate

and seamlessly integrated TBDEMs. This topobathymetric model will help future research, such as shoreline delineation, coastal inundation mapping, sediment-transport, sea-level rise, storm surge models, and tsunami impact assessment.

The following sections discuss in turn improved sea level rise models, detailed topographic/bathymetric data, and modelling of floods due to copastal subsistence.

Improved SLR Models

As more data becomes accessible on current greenhouse gas releases and global warming, climate change and modelling of the specific SLR of the Victorian coast should continue to be refined. This refinement will reduce uncertainties about the magnitude of the resulting SLR and the severity of the resulting coastal erosion. Storm bite analysis using complete coastal DEM (based on new LiDAR information) should be undertaken in key vulnerable areas to calculate the exact degree of coastal erosion and coastal depression.

Current topographical mapping along the Gippsland coast is at a scale of 1:25,000. This is insufficient to represent coastal geographical features at a scale reasonable for local decision-making. Higher resolution data would essentially help with distinguishing, with a higher degree of confidence, the areas that are potentially subject to flooding and impacts related to climate change.

Detailed Topographic/ Bathymetric Data

In this thesis (chapter 4 and 5) outlined the procedures for using typical GIS-embedded hydrological model for extracting overland flow path and boundary delineation in a coastal catchment. The study area vertical accuracy of the available LiDAR ground point dataset satisfied the requirements for catchment-wide hydrological. However, the dataset cannot meet the requirements of site-specific drainage designing practices as vertical accuracy of less than 0.1m is needed. Absolute vertical accuracy is needed to determine the relative accuracy of LiDAR derived DEM generated based on different interpolation methods those do not have enough time to process.

Accurate appraisals of hazard identified with SLR, storm flooding and coastal degradation generally rely upon an accurate representation of coastal geography. Information from existing data is not accurate enough, both horizontally and vertically. The Department of Environment Land Water and Planning (DELWP) has commenced a program to gather airborne LiDAR data along the whole Victoria coast. Information on part of the Gippsland coast has just been gathered and prepared. High-resolution LiDAR information will provide ground data with an accuracy of ± 0.15 m. The current flood-level data (held by DELWP), CSIRO storm and wave information would then be able to be plotted on new land information to more likely recognized risk over the district. The mapping ought to measure the risks regarding profundity, recurrence and term of floods. This will help local governments and give direction on which areas require critical consideration in the execution of versatile administrative procedures.

Floods due to coastal subsidence

High -resolution LiDAR data and a detailed DEM should be acquired and prepared for the Gippsland shoreline section that are threatened by coastal subsidence (entry from the entrance to the lakes). The extension of floods due to the combined effect of SLR and land subsidence should be re-modelled using the subsidence parameters outlined in the most recent CSIRO survey (Freij-Ayoub et al., 2007). This will produce a more accurate map of threatened sites and better illustrate the extent to which the Ninety Mile Beach barrier dunes could be breached.

8.6 Contribution and Closing Remarks

Reducing the risk of coastal flooding is largely based on adequate land use planning in coastal management in Australia. The goal of greater flood resilience needs the management of flood impacts in the existing developed areas and in areas that could be developed in the future. This research examined the roles and responsibilities of organizations relevant to coastal flooding. Local governments are the authorities responsible for managing the risk of coastal flooding. Furthermore, this research has developed an approach to support coast flood risk management planning using the

hydrological models incorporated into GIS, producing the required information products, using the BCSC as a research study area. The research listed in Chapter 4 supported the over land flow path process and detailed collection property discharge maps.

Chapter 4 examined the existing GIS-based hydrological model in BCSC and identified a suitable model, and then assessed the hydrological models incorporated into GIS for their ability to provide the information products needed for coastal flood risk planning. The information products required in the delineation of the floodplains of the flood-relevant GIS database are the delineation of coastal hydrographical basins and detailed river basins using conceptual hydrological modelling using the spatial data integration methods developed in Chapters 6 and 7. Developed methods have enabled local governments, such as coastal management agencies, to implement land-use planning measures for flood risk. This research used the future LiDAR coastline, hydrology, climate, and integration of infrastructure data to determine flood-prone areas in a downpour. Chapter 7 identified infrastructure at risk from coastal flooding (roads and buildings).

The developed spatial tools allow local governments to assess the completeness and quality of their flood-relevant GIS database. Therefore, using the built-in hydrological model's GIS to provide missing information products, Local Governments can use methods developed to improve flood management plans of the coastal area.

References:

ABBAS, N., WASIMI, S. A., AL-ANSARI, N. J. J. O. C. E. & ARCHITECTURE 2016. Climate Change Impacts on Water Resources of Greater Zab River, Iraq: Climate Change Impacts on Water Resources of Greater Zab River, Iraq. 10**,** 1384-1402.

ABBAS, N., WASIMI, S. A., BHATTARAI, S. & AL-ANSARI, N. 2017. The Impacts of Climate Change on Fitzroy River Basin, Queensland, Australia: The Impacts of Climate Change on Fitzroy River Basin, Queensland, Australia. *Journal of Civil Engineering and Architecture,* 11**,** 38-47.

ABBASPOUR, K. C., YANG, J., MAXIMOV, I., SIBER, R., BOGNER, K., MIELEITNER, J., ZOBRIST, J. & SRINIVASAN, R. 2007. Modelling hydrology and water quality in the pre-alpine/alpine Thur watershed using SWAT. *Journal of hydrology,* 333**,** 413-430.

ABBOTT, M. B., BATHURST, J. C., CUNGE, J. A., O'CONNELL, P. E., RASMUSSEN, J. 1986. An introduction to the European Hydrological System - Systeme Hydrologique Europeen, "SHE", 1: History and philosophy of a physically-based, distributed modelling system. *Journal of Hydrology,* 87**,** 45-59.

ABC NEWS (2016) Melbourne storms: Residents clean-up after houses damaged, motorists trapped on flooded roads, Accessed 26/5/19, Available online at https://www.abc.net.au/news/2016-12-30/melbourne-storm-floods-roads-leading-to-forty-one-rescues/8153688

ABDULLAH, A., VOJINOVIC, Z., PRICE, R. & AZIZ, N. 2012. Improved methodology for processing raw LiDAR data to support urban flood modelling–accounting for elevated roads and bridges. *Journal of Hydroinformatics,* 14**,** 253-269.

AL-MUKHTAR, M., DUNGER, V. & MERKEL, B. 2014. Assessing the impacts of climate change on hydrology of the upper reach of the spree river: Germany. *Water resources management,* 28**,** 2731-2749.

ALAMDAR, F., KALANTARI, M. & RAJABIFARD, A. J. I. J. O. D. R. R. 2017. Understanding the provision of multi-agency sensor information in disaster management: a case study on the Australian state of Victoria. 22**,** 475-493.

ALI, K. A. 2018. Geospatial Hydrological Analysis in GIS Environment for Selecting Potential Water Harvest Sites: The case of Badrah–Wasit. *Journal of University of Babylon,* 26**,** 328-337.

ALLAN, N. 2018. DEVELOPING A GIS WEB BASED INFORMATION SYSTEM FOR POPULATION DATA MANAGEMENT.

ALSHUWAIKHAT, H. M., ABUBAKAR, I. R., AINA, Y. A., ADENLE, Y. A. & UMAIR, M. 2017. The development of a GIS-based model for campus environmental sustainability assessment. *Sustainability,* 9**,** 439.

ANSELIN, L. 1995. Local indicators of spatial association—LISA. *Geographical analysis,* 27**,** 93-115.

ARNOLD, J. G., MORIASI, D. N., GASSMAN, P. W., ABBASPOUR, K. C., WHITE, M. J., SRINIVASAN, R., SANTHI, C., HARMEL, R., VAN GRIENSVEN, A. & VAN LIEW, M. W. 2012. SWAT: Model use, calibration, and validation. *Transactions of the ASABE,* 55**,** 1491-1508.

ARNOLD, J. G., SRINIVASAN, R., MUTTIAH, R. S. & WILLIAMS, J. R. 1998. Large area hydrologic modeling and assessment part I: model development 1. *JAWRA Journal of the American Water Resources Association,* 34**,** 73-89.

ASHRAF VAGHEFI, S., MOUSAVI, S., ABBASPOUR, K., SRINIVASAN, R. & YANG, H. 2014. Analyses of the impact of climate change on water resources components, drought and wheat yield in semiarid regions: Karkheh River Basin in Iran. *hydrological processes,* 28**,** 2018-2032.

ASSESSMENT, V. C. V. Future Coasts: Victorian Coastal Elevation Project.

AURROCOECHEA, I. & PETHICK, J. 1986. The Coastline-Its Physical and Legal Definition. *Int'l J. Estuarine & Coastal L.,* 1**,** 29.

AWAL, M. & IKEDA, T. 2003. Effect of elevated soil temperature on radiation-use efficiency in peanut stands. *Agricultural and forest meteorology,* 118**,** 63-74.

BABY, S. N., ARROWSMITH, C., ABBAS, N. & AL-ANSARI, N. 2018a. *Climate Change Impacts on Water Resources of AryCreek, Inverloch, Victoria*, David Publishing Company.

BABY, S. N., ARROWSMITH, C., ABBAS, N., AL-ANSARI, N. J. J. O. C. E. & ARCHITECTURE 2018b. Climate Change Impacts on Water Resources of Ary Creek, Inverloch, Victoria. 12**,** 727-740.

BABY, N., BIRRELL, B., (2012) BRADLEY, V., BRAIN, P., CAREY, M., DUFFY, M., FERRARO, S., FISHER, S., GRIGGS, D., HALL, M., JORDAN,C., LOOK, B., LENNOX, P., LYON,C., MACMILLAN, C., MANNING, I., MARTIN, H., NAVANTERI, T., NICHOLAS, A., PRICE,L., STANLEY, C., STANLEY, J., SYMMONS, M., WRIGHT, W., DISCUSSION Paper 1: The Present Environmental, Social and Economic Situation and Trends in Inverloch and Sandy Point and Surrounds, Prepared By The Project Research Team for NCCARF Project No. Si 1109, March 2012.

BAHREMAND, A., CORLUY, J., LIU, Y., DE SMEDT, F., POÓROVÁ, J. & VELCICKÁ, L. 2005. Stream flow simulation by WetSpa model in Hornad river basin, Slovakia. *Floods, from Defence to Management, Taylor-Francis Group, London***,** 415-422.

BAHREMAND, A. & DE SMEDT, F. 2008. Distributed hydrological modeling and sensitivity analysis in Torysa Watershed, Slovakia. *Water Resources Management,* 22**,** 393-408.

BAHREMAND, A., DE SMEDT, F., CORLUY, J., LIU, Y., POOROVA, J., VELCICKA, L. & KUNIKOVA, E. 2007. WetSpa model application for assessing reforestation impacts on floods in Margecany–Hornad Watershed, Slovakia. *Water Resources Management,* 21**,** 1373-1391.

BALSTRØM, T. & CRAWFORD, D. 2018. Arc-Malstrøm: A 1D hydrologic screening method for stormwater assessments based on geometric networks. *Computers & Geosciences,* 116**,** 64-73.

BANNWARTH, M., SANGCHAN, W., HUGENSCHMIDT, C., LAMERS, M., INGWERSEN, J., ZIEGLER, A. & STRECK, T. 2014. Pesticide transport simulation in a tropical catchment by SWAT. *Environmental pollution,* 191**,** 70-79.

BARNETT, W. S., EPSTEIN, D. J., CAROLAN, M. E., FITZGERALD, J., ACKERMAN, D. J. & FRIEDMAN, A. H. 2010. The state of preschool 2010. *Retrieved from http:/Inieer. org/yearbook/pdf/yearbook.*

BARTLETT, D. & SMITH, J. 2004. *GIS for coastal zone management*, CRC press.

BATELAAN, O., WANG, Z.-M. & DE SMEDT, F. 1996. An adaptive GIS toolbox for hydrological modelling. *IAHS Publications-Series of Proceedings and Reports-Intern Assoc Hydrological Sciences,* 235**,** 3-10.

BASS COAST SHIRE (2019) Welcome to Bass Coast Shire population forecasts, Accessed 15/5/19, https://forecast.id.com.au/bass-coast

BASS COAST SHIRE COUNCIL (2013) Coastal Reserve Management,

BASS COAST SHIRE COUNCIL (2018) Pioneer Bay Road & Drainage 2/2/2018, Upgradehttps://www.basscoast.vic.gov.au/services/roads-footpaths/road-and-drainage-upgrades/pioneer-bay-road-and-drainage-upgrade

BASS COAST SHIRE COUNCIL (2019) Land Subject to Inundation Overlay, Bass Coast Shire Council Planning Scheme, Accessed 1/4/19, http://planning schemes.delwp.vic.gov.au/schemes/vpps/44_04.pdf

BASS COAST SHIRE COUNCIL (2013) Accessed **27/06/2013, http://profile.id.com.au/bass-coast retrieved on 27 July 2013**

BALASUBRAMANI, K., SARAVANABAVAN, V. & KANNANDASAN, K. A Comparison of Approaches for Automated Watershed Delineation: A Case study of NagalAr Watershed. Proceedings of the National Seminar on Geospatial Technology for Resource Evaluation and Management, Department of Geography, Madurai Kamaraj University, 2012. 200-208.

BERWICK, M. 2007. The challenge of coastal governance. *Federalism and regionalism in Australia***,** 83.

BEVEN, K., CALVER, A. & MORRIS, E. 1987. The Institute of Hydrology distributed model.

BHATT, G., KUMAR, M. & DUFFY, C. J. 2014. A tightly coupled GIS and distributed hydrologic modeling framework. *Environmental modelling & software,* 62**,** 70-84.

BOWEN, G. J., PUTMAN, A., BROOKS, J. R., BOWLING, D. R., OERTER, E. J. & GOOD, S. P. 2018. Inferring the source of evaporated waters using stable H and O isotopes. *Oecologia,* 187**,** 1025-1039.

BROWN, R. R. 2005. Impediments to integrated urban stormwater management: the need for institutional reform. *Environ Manage,* 36**,** 455-68.

BRYAN, D. & CURRAN, J. 2004. Comparison of Arc Hydro and SWAT models used in watershed analysis.

BULKELEY, H. & CASTÁN BROTO, V. 2013. Government by experiment? Global cities and the governing of climate change. *Transactions of the institute of British geographers,* 38**,** 361-375.

BURROUGH, P. A. & MCDONNEL, R. 1998. Fuzzy sets and fuzzy geographical objects. *Principles of geographical information systems***,** 265-292.

BUTT, A., BUXTON, M., HAYNES, R. & LECHNER, A. Peri-urban growth, planning and bushfire in the Melbourne city-region. State of Australian Cities Conference, Perth, WA. Australian Sustainable Cities and Regions Network (ASCRN), 2009. 1-14.

CAMPAGNA, M. 2005. *GIS for sustainable development*, Crc Press.

CAMPBELL, H. J. 1990. *The use of geographical information in local authority planning departments.* University of Sheffield.

CAO, G. 2006. *Song dai fo jiao shi ji yan jiu,* Shanghai Shi, Hua dong shi fan da xue chu ban she.

CÁPIRO, N. L., STAFFORD, B. P., RIXEY, W. G., BEDIENT, P. B. & ALVAREZ, P. J. 2007. Fuel-grade ethanol transport and impacts to groundwater in a pilot-scale aquifer tank. *Water Research,* 41**,** 656-664.

CARTER, J. R. 1989. On defining the geographic information system. *Fundamentals of geographic information systems: a compendium*, 3-7.

CATON, B. & HARVEY, N. 2010. *Coastal management in Australia*, University of Adelaide Press.

CATON, B. & HARVEY, N. 2015. *Coastal management in Australia*, University of Adelaide Press.

CHAN, T. O. 1998. *The dynamics of diffusion of corporate GIS* (Doctoral dissertation).

CHARTERIS, A., SYME, W. & WALDEN, W. Urban flood modelling and mapping 2d or not 2d. 6th Conference on Hydraulics in Civil Engineering: The State of Hydraulics; Proceedings, 2001. Institution of Engineers, Australia, 355.

CHEN, M. & TUCKER, C. 2003. Comparing different approaches of catchment delineation,web: http://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.200.4002,2019.

CHENG, M., AKINBOBOLA, C., ZHEN, J., RIVERSON, J., ALVI, K. & SHOEMAKER, L. BMP Decision Support System for Evaluating Watershed Based Stormwater Management Alternatives. 2006. ASCE.

CHIEW, F., VAZE, J. & HENNESSY, K. J. 2008. *Climate data for hydrologic scenario modelling across the Murray-Darling Basin: A report to the Australian Government from the CSIRO Murray-Darling Basin Sustainable Yields Project*, CSIRO Canberra.

CHOW, V. T., MAIDMENT, D. R. & LARRY, W. 1988. Mays. Applied Hydrology. *International edition, MacGraw-Hill, Inc*, 149.

CHURCH, J. A., CLARK, P. U., CAZENAVE, A., GREGORY, J. M., JEVREJEVA, S., LEVERMANN, A., MERRIFIELD, M. A., MILNE, G. A., NEREM, R. S. & NUNN, P. D. 2013. Sea level change. PM Cambridge University Press.

CHURCH, J. A. & WHITE, N. J. 2006. A 20th century acceleration in global sea-level rise. *Geophysical research letters*, 33.

CHURCH, J. A. & WHITE, N. J. 2011. Sea-level rise from the late 19th to the early 21st century. *Surveys in geophysics*, 32, 585-602.

CIBIN, R., SUDHEER, K. & CHAUBEY, I. 2010. Sensitivity and identifiability of stream flow generation parameters of the SWAT model. *Hydrological Processes: An International Journal*, 24, 1133-1148.

CLARK, M. J. 1998. Putting water in its place: A perspective on GIS in hydrology and water management. *Hydrological Processes*, 12, 823-834.

CLARK, P. U. & WALDER, J. S. J. G. S. O. A. B. 1994. Subglacial drainage, eskers, and deforming beds beneath the Laurentide and Eurasian ice sheets. 106, 304-314.

CLIQUET, A., BOGAERT, D. & RABAUT, M. A Changing Coast: Challenge for the Environmental Policies. LITTORAL 2008, 2008, a Belgian case study.

COLOMBO, R., VOGT, J. V. & BERTOLO, F. 2001. *Deriving drainage networks and catchment boundaries at the European scale: a new approach combining digital elevation data and environmental characteristics*, European Commission, Joint Research Centre.

COMMUNITY, I. 2019. Welcome to Bass Coast Shire population forecasts. 1.

CORREA, A. C. & ADHITYAWARMA, J. The selection of appropriate satellite sources of impervious surface information for urban hydrology. *In:* SEHLKE, G., HAYES, D. F. & STEVENS, D. K., eds., 2004 Salt Lake City, UT. 819-830.

COSTABILE, P., MACCHIONE, F., NATALE, L. & PETACCIA, G. 2015. Flood mapping using LIDAR DEM. Limitations of the 1-D modeling highlighted by the 2-D approach. *Natural Hazards,* 77**,** 181-204.

Victorian Coastal Council, 2008. *Victorian coastal strategy 2008,* Victorian Coastal Council.

CRESSWELL, I. & MURPHY, H. 2017. Australia state of the environment 2016: Biodiversity, independent report to the Australian Government Minister for the Environment and Energy. *Australian Government Department of the Environment and Energy: Canberra, ACT*.

CSIRO & BOM 2007. Climate change in Australia. *CSIRO/Bureau of Meteorology/Department of Climate Change and Energy Efficiency, Canberra.*

CUSH, D. 2016. Policy and implementation: local, regional, national, international, global. Taylor & Francis.

DADSON, S. J., HOVIUS, N., CHEN, H., DADE, W. B., HSIEH, M.-L., WILLETT, S. D., HU, J.-C., HORNG, M.-J., CHEN, M.-C. & STARK, C. P. 2003. Links between erosion, runoff variability and seismicity in the Taiwan orogen. *Nature,* 426**,** 648.

DAS, S., NG, A. & PERERA, B. Development of a SWAT model in the Yarra River catchment. MODSIM2013, 20th International Congress on Modelling and Simulation. Modelling and Simulation Society of Australia and New Zealand, 2013. 2457-2464.

DE SMEDT, F., YONGBO, L. & GEBREMESKEL, S. 2000. Hydrologic modelling on a catchment scale using GIS and remote sensed land use information. *WIT Transactions on Ecology and the Environment,* 45.

DEEGAN, C. & GORDON, B. 1996. A study of the environmental disclosure practices of Australian corporations. *Accounting and business research,* 26**,** 187-199.

DELWP 2016. Victorian Floodplain Management Strategy.

DELWP December 2017. Strengthening Victoria's Marine and Coastal Management - A proposed Transition Plan.

DEVIA, G. K., GANASRI, B. & DWARAKISH, G. 2015. A review on hydrological models. *Aquatic Procedia,* 4**,** 1001-1007.

DI LUZIO, M., SRINIVASAN, R. & ARNOLD, J. G. 2004. A GIS-coupled hydrological model system for the watershed assessment of agricultural nonpoint and point sources of pollution. *Transactions in GIS,* 8**,** 113-136.

DIAZ-NIETO, J., LERNER, D., SAUL, A. & BLANKSBY, J. 2011. GIS water-balance approach to support surface water flood-risk management. *Journal of Hydrologic Engineering,* 17**,** 55-67.

DJOKIC, D. & MAIDMENT, D. R. 1993. Application of GIS network routines for water flow and transport. *Journal of Water Resources Planning and Management,* 119**,** 229-245.

DOUGLAS, I., ALAM, K., MAGHENDA, M., MCDONNELL, Y., MCLEAN, L. & CAMPBELL, J. 2008. Unjust waters: climate change, flooding and the urban poor in Africa. *Environment and urbanization,* 20**,** 187-205.

DUNCAN-JONES, H., (2013) Outh Gippsland Sentinel Times, Wonthaggi's key role in growth plan, 11/06/2013, https://sgst.com.au/2013/06/wonthaggis-key-role-in-growth-plan/

EL-SHEIMY, N., VALEO, C. & HABIB, A. 2005. Digital Terrain Modeling: Acquisition, Manipulation and Applications (Artech House Remote Sensing Library). *Norwood, MA: Artech House*.

ENNENBACH, M. W., CONCHA LARRAURI, P. & LALL, U. 2018. County-Scale Rainwater Harvesting Feasibility in the United States: Climate, Collection Area, Density, and Reuse Considerations. *JAWRA Journal of the American Water Resources Association,* 54**,** 255-274.

ERSKINE, R. H., GREEN, T. R., RAMIREZ, J. A. & MACDONALD, L. H. 2006. Comparison of grid-based algorithms for computing upslope contributing area. *Water Resources Research,* 42.

FICKLIN, D. L., LUO, Y., LUEDELING, E. & ZHANG, M. 2009. Climate change sensitivity assessment of a highly agricultural watershed using SWAT. *Journal of Hydrology,* 374**,** 16-29.

FIELD, C. B., BARROS, V., STOCKER, T. F. & DAHE, Q. 2012. *Managing the risks of extreme events and disasters to advance climate change adaptation: special report of the intergovernmental panel on climate change*, Cambridge University Press.

FRENCH, I., CECHET, B., YANG, T. & SANABRIA, A. FireDST: Fire Impact and Risk Evaluation Decision Support Tool–Model Description. 20th International Congress on Modelling and Simulation (MODSIM 2013), Adelaide, December, 2013.

FU, C., JAMES, A. L. & YAO, H. 2014. SWAT-CS: Revision and testing of SWAT for Canadian Shield catchments. *Journal of Hydrology,* 511**,** 719-735.

GALLANT, J. P. W. J. C. 2000. *Terrain analysis: principles and applications*, John Wiley & Sons.

GALLEGOS, H. A., SCHUBERT, J. E. & SANDERS, B. F. 2009. Two-dimensional, high-resolution modeling of urban dam-break flooding: A case study of Baldwin Hills, California. *Advances in water resources,* 32**,** 1323-1335.

GALLOWAY, R. & BAHR, M. 1979. What is the length of the Australian coast? *Australian geographer,* 14**,** 244-247.

GARBRECHT, J. & MARTZ, L. W. 2000. Digital elevation model issues in water resources modeling. *Hydrologic and hydraulic modeling support with geographic information systems***,** 1-28.

GARCIA, E. S. & LOÁICIGA, H. A. 2014. Sea-level rise and flooding in coastal riverine flood plains. *Hydrological Sciences Journal,* 59**,** 204-220.

GASSMAN, P. W., SADEGHI, A. M. & SRINIVASAN, R. 2014. Applications of the SWAT Model Special Section: Overview and Insights. *J Environ Qual,* 43**,** 1-8.

GEBREMESKEL, S., LIU, Y. B., DE SMEDT, F., HOFFMANN, L. & PFISTER, L. 2005. Assessing the hydrological effects of Landuse changes using distributed hydrological modelling and GIS. *International journal of river basin management,* 3**,** 261-271.

GILMER, B. & FERDAÑA, Z. 2012. Developing a framework for assessing coastal vulnerability to sea level rise in Southern New England, USA. *Resilient Cities 2.* Springer.

GITHUI, F., GITAU, W., MUTUA, F. & BAUWENS, W. 2009. Climate change impact on SWAT simulated streamflow in western Kenya. *International Journal of Climatology,* 29**,** 1823-1834.

GOODCHILD, M., PARKS, B. ,STEYAERT, L. (ed.) 1993. *Environmental Modeling with GIS,* New York: Oxford University Press.

GOODCHILD, M. F. 2003. Geographic information science and systems for environmental management. *Annual Review of Environment and Resources,* 28**,** 493-519.

GOTETI, G., FAMIGLIETTI, J. S. & ASANTE, K. 2008. A Catchment-Based Hydrologic and Routing Modeling System with explicit river channels. *Journal of Geophysical Research: Atmospheres,* 113.

GOVERNMENT, A. 2009. Climate Change Risks to Australia's Coast: A First Pass National Assessment. Department of Climate Change, Commonwealth of Australia Canberra.

GROVER, S. 1999. Perspectives of GIS modelling in hydrology. *Asia's first GIS/GPS/RS/monthly magazine (November-December)*.

GRUNBUHEL, C., WILLIAMS, L., HAYGREEN, A. & LAQNGSTON, A. 2010. Sustainable Communities Initiative in Victoria: Bass Coast Shire. CSIRO.

GÜNGÖR, Ö. & GÖNCÜ, S. 2013. Application of the soil and water assessment tool model on the Lower Porsuk Stream Watershed. *Hydrological Processes,* 27**,** 453-466.

GUPTA, V. K., WAYMIRE, E. & WANG, C. 1980. A representation of an instantaneous unit hydrograph from geomorphology. *Water Resources Research,* 16**,** 855-862.

HABIB, A., GHANMA, M., MORGAN, M. & AL-RUZOUQ, R. 2005. Photogrammetric and LiDAR data registration using linear features. *Photogrammetric Engineering & Remote Sensing,* 71**,** 699-707.

HAILE, A. T. & RIENTJES, T. 2005. Effects of LiDAR DEM resolution in flood modelling: A model sensitivity study for the city of Tegucigalpa, Honduras. *Isprs wg iii/3, iii/4,* 3**,** 12-14.

HALL, J. W., SAYERS, P. B., WALKDEN, M. J. & PANZERI, M. 2006. Impacts of climate change on coastal flood risk in England and Wales: 2030–2100. *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences,* 364**,** 1027-1049.

HALLEGATTE, S., GREEN, C., NICHOLLS, R. J. & CORFEE-MORLOT, J. J. N. C. C. 2013. Future flood losses in major coastal cities. 3**,** 802.

HANSSON, K., DANIELSON, M. & EKENBERG, L. 2008. A framework for evaluation of flood management strategies. *Journal of environmental management,* 86**,** 465-480.

HANSSON, K., HELLMAN, F., GRAUERT, M. & LARSEN, M. 2010. Methods to predict and handle flooding on highways. *The blue spot concept. Report,* 181.

HARDAKER, P. & COLLIER, C. 2013. Flood risk from extreme events (FREE)—a national environment research council directed programme. *Quarterly Journal of the Royal Meteorological Society,* 139**,** 281-281.

HARVEY, D. 2017. Conceptual and measurement problems in the cognitive-behavioral approach to location theory. *Routledge Revivals: Behavioral Problems in Geography (1969).* Routledge.

HE, Y., LIN, K. & CHEN, X. 2013. Effect of land use and climate change on runoff in the Dongjiang Basin of South China. *Mathematical Problems in Engineering,* 2013.

HELLER, N. E. & ZAVALETA, E. S. 2009. Biodiversity management in the face of climate change: a review of 22 years of recommendations. *Biological conservation,* 142**,** 14-32.

HINE, R. G., HINE, D. L., RIZZI, J. D., KIESOW III, K. A., BURCHAM, R. & STUTZ, W. A. 2017. Wave power. Google Patents.

HODGSON, M. E., JENSEN, J., RABER, G., TULLIS, J., DAVIS, B. A., THOMPSON, G. & SCHUCKMAN, K. 2005. An evaluation of lidar-derived elevation and terrain slope in leaf-off conditions. *Photogrammetric Engineering & Remote Sensing,* 71**,** 817-823.

HOEGH-GULDBERG, O. 1999. Climate change, coral bleaching and the future of the world's coral reefs. *Marine and freshwater research,* 50**,** 839-866.

HOLDSTOCK, D. A. 2016. *Strategic GIS planning and management in local government*, CRC Press.

HOWARI, F. M., SHERIF, M. M., SINGH, V. P. & AL ASAM, M. S. 2007. Application of GIS and remote sensing techniques in identification, assessment and development of groundwater resources. *Groundwater.* Springer.

HUANG, J., ZHANG, X., XIN, Q., SUN, Y., ZHANG, P. J. I. J. O. P. & SENSING, R. 2019. Automatic building extraction from high-resolution aerial images and LiDAR data using gated residual refinement network. 151**,** 91-105.

HUNTER, J. G., ENGEL, B. A. & QUANSAH, J. E. Web-based low impact development decision support tool for watershed planning. 2010 San Francisco, CA. 484-495.

HURLIMANN, A., BARNETT, J., FINCHER, R., OSBALDISTON, N., MORTREUX, C. & GRAHAM, S. 2014. Urban planning and sustainable adaptation to sea-level rise. *Landscape and Urban Planning,* 126**,** 84-93.

JACOBSON, C. R. 2011. Identification and quantification of the hydrological impacts of imperviousness in urban catchments: A review. *Journal of environmental management,* 92**,** 1438-1448.

JEONG, H., KIM, H., JANG, T. & PARK, S. 2016. Assessing the effects of indirect wastewater reuse on paddy irrigation in the Osan River watershed in Korea using the SWAT model. *Agricultural Water Management,* 163**,** 393-402.

KAPLAN, B. & DUCHON, D. 1988. Combining qualitative and quantitative methods in information systems research: a case study. *MIS quarterly***,** 571-586.

KEENAN, T., CLEUGH, H., HOLLIS, A., DAY, K. A. & HOLPER, P. N. 2011. *Climate science update: a report to the 2011 Garnaut Review*, Citeseer.

KENCHINGTON, R. & CRAWFORD, D. 1993. On the meaning of integration in coastal zone management. *Ocean & Coastal Management,* 21**,** 109-127.

KOUWEN, N. 1988. WATFLOOD: a micro-computer based flood forecasting system based on real-time weather radar. *Canadian Water Resources Journal,* 13**,** 62-77.

KRYSANOVA, V. & WHITE, M. J. H. S. J. 2015. Advances in water resources assessment with SWAT—an overview. 60**,** 771-783.

KUNDAPURA, S., KOMMOJU, R. & VERMA, I. 2018. Assessment of Changes in Wetland Storage in Gurupura River Basin of Karnataka, India, Using Remote. *Water Resources and Environmental Engineering II***,** 57.

LATHROP, R., AUERMULLER, L., TRIMBLE, J. & BOGNAR, J. J. I. I. J. O. G.-I. 2014. The application of WebGIS tools for visualizing coastal flooding vulnerability and planning for resiliency: The New Jersey experience. 3**,** 408-429.

L'Homme, M.C., 2004. A Lexico-semantic Approach to the Structuring of Terminology. In Proceedings of CompuTerm 2004: 3rd International Workshop on Computational Terminology (pp. 7-14). LAI, F. H., SHOEMAKER, L. & RIVERSON, J. Framework design for BMP placement in Urban watersheds. 2005 Anchorage, AK. 185.

LEAVESLEY, G. H. 1994. Modeling the effects of climate change on water resources—a review. *Assessing the Impacts of Climate Change on Natural Resource Systems.* Springer.

LEE, J. G. & HEANEY, J. P. 2003. Estimation of urban imperviousness and its impacts on storm water systems. *Journal of Water Resources Planning and Management,* 129**,** 419-426.

LEMPERT, R., KALRA, N., PEYRAUD, S., MAO, Z., TAN, S. B., CIRA, D. & LOTSCH, A. 2013. *Ensuring robust flood risk management in Ho Chi Minh City,* The World Bank.

LETHLEAN, H., VAN DONGEN, W. F., KOSTOGLOU, K., GUAY, P.-J. & WESTON, M. A. 2017. Joggers cause greater avian disturbance than walkers. *Landscape and Urban Planning,* 159**,** 42-47.

LIN, X., PARKS, D., PAINTER, J., HUNT, C. M., STIRNADEL-FARRANT, H. A., CHENG, J., MENIUS, A. & LEE, K. 2012. Validation of multivariate outlier detection analyses used to identify potential drug-induced liver injury in clinical trial populations. *Drug safety,* 35**,** 865-875.

LIU, H. & WANG, L. 2008. Mapping detention basins and deriving their spatial attributes from airborne LiDAR data for hydrological applications. *Hydrological Processes: An International Journal,* 22**,** 2358-2369.

LIU, Q.-M., WANG, Y.-Q. J. J. O. I. M. I. O. A. & HUSBANDRY, A. 2005a. RESEARCH ON THE DTM SPACIAL INTERPOLATION TECHNIQUE BASED ON THE GEOLOGICAL STATISTICS [J]. 4.

LIU, X., AI, Y., ZHANG, F., LU, S., ZENG, X. & FAN, M. 2005b. Crop production, nitrogen recovery and water use efficiency in rice–wheat rotation as affected by non-flooded mulching cultivation (NFMC). *Nutrient Cycling in Agroecosystems,* 71**,** 289-299.

LIU, Y., CORLUY, J., BAHREMAND, A., DE SMEDT, F., POOROVA, J. & VELCICKA, L. 2006. Simulation of runoff and phosphorus transport in a carpathian catchment, Slovakia. *River Research and Applications,* 22**,** 1009-1022.

LIU, Y. & DE SMEDT, F. 2004. WetSpa extension, a GIS-based hydrologic model for flood prediction and watershed management. *Vrije Universiteit Brussel, Belgium***,** 1-108.

LIU, Z. Y. & TODINI, E. 2002. Towards a comprehensive physically-based rainfall-runoff model. *Hydrology and Earth System Sciences,* 6**,** 859-881.

LONGLEY, P. A., GOODCHILD, M. F., MAGUIRE, D. J. & RHIND, D. W. 2005. *Geographic information systems and science,* John Wiley & Sons.

LOUGH, J. M. & HOBDAY, A. J. 2011. Observed climate change in Australian marine and freshwater environments. *Marine and Freshwater Research,* 62**,** 984-999.

MA, R.-M., LI, Z.-X., CAI, C.-F. & WANG, J.-G. 2014. The dynamic response of splash erosion to aggregate mechanical breakdown through rainfall simulation events in Ultisols (subtropical China). *Catena,* 121**,** 279-287.

MAATHUIS, B. & WANG, L. 2006. Digital elevation model based hydro-processing. *Geocarto International,* 21**,** 21-26.

MACINTOSH, A. 2012. Coastal adaptation planning: a case study on Victoria, Australia. *Australia, Canberra, ANU Centre for Climate Law and Policy, ANU College of Law*.

MAKSIMOVIĆ, Č., PRODANOVIĆ, D., BOONYA-AROONNET, S., LEITÃO, J. P., DJORDJEVIĆ, S. & ALLITT, R. J. J. O. H. R. 2009. Overland flow and pathway analysis for modelling of urban pluvial flooding. 47**,** 512-523.

MALLAWAARACHCHI, T., WALKER, P., YOUNG, M. D., SMYTH, R. E., LYNCH, H. & DUDGEON, G. 1996. GIS-based integrated modelling systems for natural resource management. *Agricultural Systems,* 50**,** 169-189.

MANFREDA, S., DI LEO, M. & SOLE, A. 2011. Detection of flood-prone areas using digital elevation models. Journal of Hydrologic Engineering, 16, 781-790.

MARCY, D., BROOKS, W., DRAGANOV, K., HADLEY, B., HAYNES, C., HEROLD, N., MCCOMBS, J., PENDLETON, M., RYAN, S. & SCHMID, K. 2011. New mapping tool and techniques for visualizing sea level rise and coastal flooding impacts. *Solutions to Coastal Disasters 2011*.

MASON, P. 2015. Tourism impacts, planning and management, Routledge.

MATA, M. 2017. 20,000 Properties Could Flood Melbourne,web: https://www.yourinvestmentpropertymag.com.au/news/20000-properties-could-flood-melbourne-243700.aspx, 2017.

MCDOUGALL, K., LIU, X., BASNET, B. & APAN, A. Digital elevation model accuracy requirements for catchment management. 2008. Spatial Sciences Institute.

MCDOUGALL, S. 2006. *A new continuum dynamic model for the analysis of extremely rapid landslide motion across complex 3D terrain.* University of British Columbia.

MCGUIRE, M. P., ROBERGE, M. C. & LIAN, J. HydroCloud: A cloud-based system for hydrologic data integration and analysis. 2014 Fifth International Conference on Computing for Geospatial Research and Application, 2014. IEEE, 9-16.

MCKENZIE, F. J. A. J. O. R. S., THE 2006. Rural Complexity, Regional Diversity: Some Observations from Victoria's Regional Matters Atlas 2005. 12**,** 343.

MERWADE, V. 2018. Flood Modeling Within the Context of Sustainable Water Resources Management.

MERWADE, V., COOK, A. & COONROD, J. 2008. GIS techniques for creating river terrain models for hydrodynamic modeling and flood inundation mapping. *Environmental Modelling & Software,* 23**,** 1300-1311.

MESSNER, F. & MEYER, V. 2006. Flood damage, vulnerability and risk perception–challenges for flood damage research. *Flood risk management: hazards, vulnerability and mitigation measures.* Springer.

MOHAMMADI, H. 2008. *The Integration of multi-source spatial datasets in the context of SDI Initiatives*, University of Melbourne, Centre for Spatial Data Infrastructures and Land Administration, Department of Geomatics.

MONASH, U. O. 2012. - NOTES AND DRAWINGS TO GIVE AN OVERVIEW OF THE CURRENT PLANNING SCHEME AND BUILT ENVIRONMENT CONDITIONS.

MONREAL, N. L.-R., LÓPEZ-VICENTE, M., ROMERO, M. E. N., OJANGUREN, R., ADÁN, J. A. L., ERREA, P., MUÑOZ, D. R., FLAÑO, P. R., KHORCHANI, M. & VADILLO, J. A. 2018. Catchment based hydrology under post farmland

abandonment scenarios. *Cuadernos de investigación geográfica/Geographical Research Letters*, 503-534.

MOORE, I. D., GRAYSON, R. B. & LADSON, A. R. 1991. Digital terrain modelling: a review of hydrological, geomorphological, and biological applications. *Hydrological Processes,* 5, 3-30.

MORIASI, D. N., ARNOLD, J. G., VAN LIEW, M. W., BINGNER, R. L., HARMEL, R. D. & VEITH, T. L. 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Transactions of the ASABE,* 50, 885-900.

MORRIS, S., COBBY, D., ZAIDMAN, M. & FISHER, K. 2018. Modelling and mapping groundwater flooding at the ground surface in Chalk catchments. *Journal of Flood Risk Management,* 11, S251-S268.

MOTE, P., PETERSEN, A., REEDER, S., SHIPMAN, H. & WHITELY BINDER, L. 2008. Sea level rise in the coastal waters of Washington State.

NDOMBA, P., MTALO, F. & KILLINGTVEIT, A. 2008. SWAT model application in a data scarce tropical complex catchment in Tanzania. *Physics and Chemistry of the Earth, Parts A/B/C,* 33, 626-632.

NEITSCH, S. L., ARNOLD, J. G., KINIRY, J. R. & WILLIAMS, J. R. 2011. Soil and water assessment tool theoretical documentation version 2009. Texas Water Resources Institute.

NEWS, A. 2016. Melbourne storms: Residents clean-up after houses damaged, motorists trapped on flooded roads.

NICHOLLS, R. J. 2004. Coastal flooding and wetland loss in the 21st century: changes under the SRES climate and socio-economic scenarios. *Global Environmental Change,* 14, 69-86.

NICHOLLS, R. J., HOOZEMANS, F. M. & MARCHAND, M. 1999. Increasing flood risk and wetland losses due to global sea-level rise: regional and global analyses. *Global Environmental Change,* 9, S69-S87.

NOH, M.-J., HOWAT, I. M. J. G. & SENSING, R. 2015. Automated stereo-photogrammetric DEM generation at high latitudes: Surface Extraction with TIN-based Search-space Minimization (SETSM) validation and demonstration over glaciated regions. 52, 198-217.

NOONE, K. J. J. R. D. K. N. U. S., MANAGING OCEAN ENVIRONMENTS IN A CHANGING CLIMATE. SUSTAINABILITY & ECONOMIC PERSPECTIVES, A. 2013. Sea-Level Rise. 97-126.

NYENJE, P. M. & BATELAAN, O. 2009. Estimating the effects of climate change on groundwater recharge and baseflow in the upper Ssezibwa catchment, Uganda. *Hydrological sciences journal,* 54, 713-726.

OLAYA, V. & CONRAD, O. 2009. Geomorphometry in SAGA. *Developments in soil science,* 33, 293-308.

OLIVERA, F. & MAIDMENT, D. 1999. Geographic Information Systems (GIS)-based spatially distributed model for runoff routing. *Water Resources Research,* 35, 1155-1164.

ONSRUD, H. J., PINTO, J. K. & AZAD, B. 1992. Case study research methods for geographic information systems. *URISA journal,* 4, 32-44.

ORYSPAYEV, D., SUGUMARAN, R., DEGROOTE, J. & GRAY, P. 2012. LiDAR data reduction using vertex decimation and processing with GPGPU and multicore CPU technology. *Computers & Geosciences,* 43, 118-125.

PECHLIVANIDIS, I., JACKSON, B., MCINTYRE, N. & WHEATER, H. 2011. Catchment scale hydrological modelling: a review of model types, calibration approaches and uncertainty analysis methods in the context of recent developments in technology and applications. *Global NEST journal,* 13**,** 193-214.

PETROSELLI, A. J. G. & SENSING, R. 2012. LIDAR data and hydrological applications at the basin scale. 49**,** 139-162.

PHAM, B. T., BUI, D. T., PRAKASH, I. & DHOLAKIA, M. 2017. Hybrid integration of Multilayer Perceptron Neural Networks and machine learning ensembles for landslide susceptibility assessment at Himalayan area (India) using GIS. *Catena,* 149**,** 52-63.

PILLORA, S. 2011. Australian Local Government and Climate Change Working Paper, web:https://opus.lib.uts.edu.au/bitstream/10453/42075/3/LG-Climate-Change.pdf, 2010.

PıNARBAŞı, K., GALPARSORO, I., BORJA, Á., STELZENMÜLLER, V., EHLER, C. N. & GIMPEL, A. 2017. Decision support tools in marine spatial planning: present applications, gaps and future perspectives. *Marine Policy,* 83**,** 83-91.

PIRRONE, N., TROMBINO, G., CINNIRELLA, S., ALGIERI, A., BENDORICCHIO, G., PALMERI, L. 2005. The Driver-Pressure-State-Impact-Response (DPSIR) approach for integrated catchment-coastal zone management: Preliminary application to the Po catchment-Adriatic Sea coastal zone system. *Regional Environmental Change,* 5**,** 111-137.

PITTMAN, S. J., COSTA, B. & WEDDING, L. M. 2013. LiDAR applications. *Coral reef remote sensing.* Springer.

POPPENGA, S. & WORSTELL, B. 2015. Evaluation of airborne Lidar elevation surfaces for propagation of coastal inundation: the importance of hydrologic connectivity. *Remote Sensing,* 7**,** 11695-11711.

POPPENGA, S. K., WORSTELL, B. B., EVANS, G. A., DANIELSON, J. J., BROCK, J. C. & HEIDEMANN, H. K. Hydrologicenforcement of lidar DEMs in select reaches of the Delaware River Basin. Proceedings of the Association of American Geographers Annual Meeting, 2014.

POPPENGA, S. K., WORSTELL, B. B., STOKER, J. M. & GREENLEE, S. K. 2010. Using selective drainage methods to extract continuous surface flow from 1-meter LiDAR-derived digital elevation data. U. S. Geological Survey.

POURALI, S. 2014. Developing a spatial approach to support local flood-risk-based land use planning, web: https://researchbank.rmit.edu.au/view/rmit:160800, 2014.

POURALI, S., ARROWSMITH, C., CHRISMAN, N. & MATKAN, A. 2014a. Vertical accuracy assessment of LiDAR ground points using minimum distance approach. *Proceedings Research@ Locate,* 14.

POURALI, S. H., ARROWSMITH, C., MITCHELL, D. & MATKAN, A. 2014b. Modelling An Overland Water Flow Path In An Urban Catchment Using GIS. *Geoinformatica: An International Journal,* 4.

PRODANOVIĆ, D., STANIĆ, M., MILIVOJEVIĆ, V., SIMIĆ, Z. & ARSIĆ, M. J. J. O. S. S. F. C. M. 2009. DEM-based GIS algorithms for automatic creation of hydrological models data. 3**,** 64-85.

QUINN, P., BEVEN, K. & LAMB, R. 1995. The in (a/tan/β) index: How to calculate it and how to use it within the topmodel framework. *Hydrological processes,* 9**,** 161-182.

RAJABIFARD, A., FEENEY, M.-E. F. & WILLIAMSON, I. P. 2002. Future directions for SDI development. *International Journal of Applied Earth Observation and Geoinformation,* 4**,** 11-22.

RATA, M., BLIDARU, T. V. & AGACHI, P. S. GIS data modeling in water management decision support systems. Automation, Quality and Testing, Robotics, 2014 IEEE International Conference on, 2014. IEEE, 1-6.

RAVI, R., LIN, Y.-J., ELBAHNASAWY, M., SHAMSELDIN, T. & HABIB, A. 2018. Bias Impact Analysis and Calibration of Terrestrial Mobile LiDAR System With Several Spinning Multibeam Laser Scanners. *IEEE Transactions on Geoscience and Remote Sensing*.

REFICE, A., PASQUARIELLO, G., D'ADDABBO, A., BOVENGA, F., NUTRICATO, R., CAPOLONGO, D., LEPERA, A., PIETRANERA, L., MANFREDA, S. & CANTISANI, A. Inundation monitoring through high-resolution SAR/InSAR data and 2D hydraulic simulations. Proceedings of EARSel, 2013.

REIDSMA, P., KÖNIG, H., FENG, S., BEZLEPKINA, I., NESHEIM, I., BONIN, M., SGHAIER, M., PURUSHOTHAMAN, S., SIEBER, S., VAN ITTERSUM, M. K. & BROUWER, F. 2011. Methods and tools for integrated assessment of land use policies on sustainable development in developing countries. *Land Use Policy,* 28**,** 604-617.

RINDERER, M., VAN MEERVELD, H. & SEIBERT, J. J. W. R. R. 2014. Topographic controls on shallow groundwater levels in a steep, prealpine catchment: When are the TWI assumptions valid? 50**,** 6067-6080.

ROSTAMIAN, R., JALEH, A., AFYUNI, M., MOUSAVI, S. F., HEIDARPOUR, M., JALALIAN, A. & ABBASPOUR, K. C. 2008. Application of a SWAT model for estimating runoff and sediment in two mountainous basins in central Iran. *Hydrological Sciences Journal,* 53**,** 977-988.

ROWLEY, R. J., KOSTELNICK, J. C., BRAATEN, D., LI, X. & MEISEL, J. 2007. Risk of rising sea level to population and land area. *Eos, Transactions American Geophysical Union,* 88**,** 105-107.

ROY, A. H., WENGER, S. J., FLETCHER, T. D., WALSH, C. J., LADSON, A. R., SHUSTER, W. D., THURSTON, H. W. & BROWN, R. R. 2008. Impediments and solutions to sustainable, watershed-scale urban stormwater management: lessons from Australia and the United States. *Environmental management,* 42**,** 344-359.

ŠAMANOVIĆ, S., MEDAK, D. & KUNŠTEK, D. 2017. Influence of pit removal algorithms on surface runoff simulation. *Građevinar,* 69**,** 183-198.

SAMPATH, A. & SHAN, J. 2007. Building boundary tracing and regularization from airborne LiDAR point clouds. *Photogrammetric Engineering & Remote Sensing,* 73**,** 805-812.

SANADHYA, P., GIRONÁS, J. & ARABI, M. 2014. Global sensitivity analysis of hydrologic processes in major snow-dominated mountainous river basins in Colorado. *Hydrological processes,* 28**,** 3404-3418.

SANTHI, C., ARNOLD, J., WILLIAMS, J., HAUCK, L. & DUGAS, W. 2001. Application of a watershed model to evaluate management effects on point and nonpoint source pollution. *Transactions of the ASAE,* 44**,** 1559.

SARKER, M. & SIVERTUN, A. 2011. GIS and RS combined analysis for flood prediction mapping–a case study of Dhaka city corporation, Bangladesh. *Int J Environ Protect,* 1**,** 30-42.

SCHILLING, K. E., JHA, M. K., ZHANG, Y. K., GASSMAN, P. W. & WOLTER, C. F. 2008. Impact of land use and land cover change on the water balance of a large agricultural watershed: Historical effects and future directions. *Water Resources Research,* 44.

SCHNEIDER, S. H. & CHEN, R. S. 1980. Carbon dioxide warming and coastline flooding: physical factors and climatic impact. *Annual review of energy,* 5**,** 107-140.

SCHUOL, J. & ABBASPOUR, K. 2007. A daily weather generator for predicting rainfall and maximum–minimum temperature using monthly statistics based on a half-degree climate grid. *Ecol. Model,* 201**,** 301-311.

SCHUOL, J., ABBASPOUR, K. C., SRINIVASAN, R. & YANG, H. 2008. Estimation of freshwater availability in the West African sub-continent using the SWAT hydrologic model. *Journal of hydrology,* 352**,** 30-49.

SERRAO-NEUMANN, S., HARMAN, B. P. & LOW CHOY, D. 2013. The Role of Anticipatory Governance in Local Climate Adaptation: Observations from Australia. *Planning Practice & Research,* 28**,** 440-463.

SETEGN, S. G., SRINIVASAN, R. & DARGAHI, B. 2008. Hydrological modelling in the Lake Tana Basin, Ethiopia using SWAT model. *The Open Hydrology Journal,* 2.

SHARIFI, M., ZUCCA, A., GENELETTI, D. & ABDULLAH, A. 2009. Integrated planning and decision support systems: concepts and application to a site selection problem. *Spatial decision support for urban and environmental planning. A collection of case studies. Arah Publications, Kuala Lumpur***,** 5-31.

SHNEIDERMAN, B. 2010. *Designing the user interface: strategies for effective human-computer interaction*, Pearson Education India.

SIART, C., BUBENZER, O. & EITEL, B. 2009. Combining digital elevation data (SRTM/ASTER), high resolution satellite imagery (Quickbird) and GIS for geomorphological mapping: A multi-component case study on Mediterranean karst in Central Crete. *Geomorphology,* 112**,** 106-121.

SINGH, S., KUMAR, R., BHARDWAJ, A., KUMAR, R., SINGH, A. J. I. J. O. H. S. & TECHNOLOGY 2018. Changing climate and glacio-hydrology: a case study of Shaune Garang basin, Himachal Pradesh. 8**,** 258-272.

SINGH, V. P. & FIORENTINO, M. 2013. *Geographical information systems in hydrology*, Springer Science & Business Media.

SINGH, V. P. & WOOLHISER, D. A. 2002. Mathematical modeling of watershed hydrology. *Journal of hydrologic engineering,* 7**,** 270-292.

SMALL, C. & NICHOLLS, R. J. 2003. A global analysis of human settlement in coastal zones. *Journal of coastal research***,** 584-599.

SOMAN, K., CHAKRAVARTHY, S. & YARTSEV, M. 2018. A Hierarchical Anti-Hebbian Network Model for the Formation of Spatial Cells in Three-Dimensional Space. *bioRxiv***,** 264366.

SOPHOCLEOUS, M. & PERKINS, S. P. 2000. Methodology and application of combined watershed and ground-water models in Kansas. *Journal of Hydrology,* 236**,** 185-201.

SØRENSEN, R. & SEIBERT, J. 2007. Effects of DEM resolution on the calculation of topographical indices: TWI and its components. *Journal of Hydrology,* 347**,** 79-89.

SOULIS, K. X., MANOLAKOS, D., ANAGNOSTOPOULOS, J. & PAPANTONIS, D. J. R. E. 2016. Development of a geo-information system embedding a spatially distributed hydrological model for the preliminary assessment of the hydropower potential of historical hydro sites in poorly gauged areas. 92**,** 222-232.

STANLEY, J., BIRRELL, R. & BRAIN, P. 2013. What would a climate-adapted settlement look like in 2030? A case study of Inverloch and Sandy Point.

STERR, H., KLEIN, R. & REESE, S. 2000. Climate change and coastal zones: an overview of the state-of-the-art on regional and local vulnerability assessment. Nota di Lavoro, Fondazione Eni Enrico Mattei.

STEWART, B. 2015. Measuring what we manage–the importance of hydrological data to water resources management. *Proceedings of the International Association of Hydrological Sciences,* 366**,** 80-85.

SUGUMARAN, R. & DEGROOTE, J. 2010. *Spatial decision support systems: Principles and practices,* Crc Press.

SUI, D. & MAGGIO, R. 1999. Integrating GIS with hydrological modeling: practices, problems, and prospects. *Computers, environment and urban systems,* 23**,** 33-51.

SUI, D., MAGGIO, R. J. C., ENVIRONMENT & SYSTEMS, U. 1999. Integrating GIS with hydrological modeling: practices, problems, and prospects. 23**,** 33-51.

SUNDARAM, S. & YARRAKULA, K. 2017. *Comparison and extraction of watershed using Arc swat and Arc hydro from high resolution digital elevation model*.

TACHIKAWA, Y., SHIIBA, M. & TAKASAO, T. 1994. DEVELOPMENT OF A BASIN GEOMORPHIC INFORMATION SYSTEM USING A TIN-DEM DATA STRUCTURE 1. *JAWRA Journal of the American Water Resources Association,* 30**,** 9-17.

TAIT, M. G. 2005. Implementing geoportals: applications of distributed GIS. *Computers, Environment and Urban Systems,* 29**,** 33-47.

TEELING, E. C., SPRINGER, M. S., MADSEN, O., BATES, P., O'BRIEN, S. J. & MURPHY, W. J. 2005. A molecular phylogeny for bats illuminates biogeography and the fossil record. *Science,* 307**,** 580-584.

THOM, R., WILLIAMS, G. & DIEFENDERFER, H. 2005. Balancing the need to develop coastal areas with the desire for an ecologically functioning coastal environment: Is net ecosystem improvement possible? *Restoration Ecology,* 13**,** 193-203.

THOMAS, C. & SAPPINGTON, N. 2009. *GIS for Decision Support and Public Policy Making,* ESRI Press.

TIWARI, T., LIDMAN, F., LAUDON, H., LIDBERG, W. & ÅGREN, A. M. 2017. GIS-based prediction of stream chemistry using landscape composition, wet areas, and hydrological flow pathways. *Journal of Geophysical Research: Biogeosciences,* 122**,** 65-79.

TREUER, G. A. 2018. The psychology of Miami's struggle to adapt to sea-level rise. *Bulletin of the Atomic Scientists,* 74**,** 155-159.

TRKMAN, P. & MCCORMACK, K. 2009. Supply chain risk in turbulent environments—A conceptual model for managing supply chain network risk. *International Journal of Production Economics,* 119**,** 247-258.

TUTEJA, N. K., VAZE, J., TENG, J. & MUTENDEUDZI, M. 2007. Partitioning the effects of pine plantations and climate variability on runoff from a large catchment in southeastern Australia. *Water Resources Research,* 43.

USSYSHKIN, R. V. & SMITH, B. Performance analysis of ALTM 3100EA: Instrument specifications and accuracy of lidar data. ISPRS Commission I Symposium, Paris; Proceedings, part B, 2006. Citeseer.

VASEY-ELLIS, N. 2009. Planning for climate change in coastal Victoria. *Urban Policy and Research,* 27**,** 157-169.

VAZE, J. & TENG, J. 2007. High resolution LIDAR DEM–How good is it. *Modelling and Simulation***,** 692-698.

VELLINGA, M. M., OUDE ENGBERINK, R. D., SEEWANN, A., POUWELS, P. J., WATTJES, M. P., VAN DER POL, S. M., PERING, C., POLMAN, C. H., DE VRIES, H. E. & GEURTS, J. J. 2008. Pluriformity of inflammation in multiple sclerosis shown by ultra-small iron oxide particle enhancement. *Brain,* 131**,** 800-807.

VONK, G., GEERTMAN, S. & SCHOT, P. 2007. New technologies stuck in old hierarchies: The diffusion of geo-information technologies in dutch public organizations. *Public Administration Review,* 67**,** 745-756.

WALKER, S. C., HURVITZ, P. M., LEITH, J., RODRIGUEZ, F. I. & ENDLER, G. C. 2016. Evidence-based program service deserts: A Geographic Information Systems (GIS) approach to Identifying service gaps for state-level implementation planning. *Administration and Policy in Mental Health and Mental Health Services Research,* 43**,** 850-860.

WALSH, K., BERGER, J.-F., ROBERTS, C. N., VANNIERE, B., GHILARDI, M., BROWN, A. G., WOODBRIDGE, J., LESPEZ, L., ESTRANY, J. & GLAIS, A. J. T. H. 2019. Holocene demographic fluctuations, climate and erosion in the Mediterranean: A meta data-analysis. 29**,** 864-885.

WANG, X. & MCALLISTER, R. 2011. *Adapting to heatwaves and coastal flooding*, CSIRO Publishing, Collingwood, Vic.

WANG, X. & XIE, H. 2018. A review on applications of remote sensing and geographic information systems (GIS) in water resources and flood risk management. Multidisciplinary Digital Publishing Institute.

WANG, Y., LI, Z., TANG, Z. & ZENG, G. 2011. A GIS-based spatial multi-criteria approach for flood risk assessment in the Dongting Lake Region, Hunan, Central China. *Water resources management,* 25**,** 3465-3484.

WASKO, C. & SHARMA, A. 2015. Steeper temporal distribution of rain intensity at higher temperatures within Australian storms. *Nature Geoscience,* 8**,** 527.

WATER, M. 2007. Port Phillip and Westernport regional river health strategy. *Melbourne Water, Melbourne, Victoria*.

WEBER, F.-A., VOEGELIN, A. & KRETZSCHMAR, R. 2009. Multi-metal contaminant dynamics in temporarily flooded soil under sulfate limitation. *Geochimica et Cosmochimica Acta,* 73**,** 5513-5527.

WELDON, D., REASON, C. J. T. & CLIMATOLOGY, A. 2014. Variability of rainfall characteristics over the South Coast region of South Africa. 115**,** 177-185.

WENG, Q. J. E. M. 2001. Modeling urban growth effects on surface runoff with the integration of remote sensing and GIS. 28**,** 737-748.

WESCOTT, G. 1998. Reforming coastal management to improve community participation and integration in Victoria, Australia. *Coastal Management,* 26**,** 3-15.

WESCOTT, G. 2004. The Theory and Practice of Coastal Area Planning: Linking Strategic Planning to Local Communities. *Coastal Management,* 32**,** 95-100.

WHEELER, P. & PETERSON, J. J. C. M. 2010. Exploring stakeholder views regarding spatial information and enabling technology use for ICZM: A case study from Victoria, Australia. 38**,** 1-21.

WHEELER, P. J., PETERSON, J. A. & GORDON-BROWN, L. N. 2011. Spatial decision support for integrated coastal zone management (ICZM) in Victoria, Australia: constraints and opportunities. *Journal of Coastal Research,* 27**,** 296-317.

WHEELER, P. J., PETERSON, J.A., GORDON-BROWN, L.N. 2010. Spatial Decision Support for Integrated Coastal Zone Management (ICZM) in Victoria, Australia: Constraints and Opportunities. *Journal of Coastal Research,* 00(0)**,** 1-22.

WHITE, T. 2016. Thirty per cent of the entire state: Victorian floods, 2011. *Incident Management in Australasia: Lessons Learnt from Emergency Responses***,** 141.

WIECZOREK, W. F. & DELMERICO, A. M. 2009. Geographic information systems. *Wiley Interdisciplinary Reviews: Computational Statistics,* 1**,** 167-186.

WOODGATE, P. & COPPA, I. 2008. VIRTUAL AUSTRALIA-THE NEXT GENERATION OF RESEARCH INVESTMENTS TO HELP SHAPE A NATION. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences,* 37**,** 1085-1088.

WU, Y., GIRI, S., QIU, Z. J. I. S. & RESEARCH, W. C. 2016. Understanding the spatial distribution of hydrologic sensitive areas in the landscape using soil topographic index approach. 4**,** 278-283.

XIAN, S., LIN, N. & HATZIKYRIAKOU, A. 2015. Storm surge damage to residential areas: a quantitative analysis for Hurricane Sandy in comparison with FEMA flood map. *Natural Hazards,* 79**,** 1867-1888.

XU, Z., ITO, K., SCHULTZ, G. & LI, J. 2001. Integrated hydrologic modeling and GIS in water resources management. *Journal of Computing in Civil Engineering,* 15**,** 217-223.

YANG, B. J. A. G. 2016. GIS based 3-D landscape visualization for promoting citizen's awareness of coastal hazard scenarios in flood prone tourism towns. 76**,** 85-97.

YIN, R. K. 2003. Applications of case study research. Applied social research methods series. *Thousand Oaks: Sage Publications. Yu, KH (2013). Institutionalization in the context of institutional pluralism: Politics as a generative process, Organization Studies,* 34**,** 105-131.

ZERGER, A. & WEALANDS, S. 2004. Beyond modelling: linking models with GIS for flood risk management. *Natural Hazards,* 33**,** 191-208.

ZHANG, S. & PAN, B. 2014a. An urban storm-inundation simulation method based on GIS. *Journal of hydrology,* 517**,** 260-268.

ZHANG, S. & PAN, B. J. J. O. H. 2014b. An urban storm-inundation simulation method based on GIS. 517**,** 260-268.

ZHANG, X.-S., SRINIVASAN, R. & VAN LIEW, M. 2008. Multi-site calibration of the SWAT model for hydrologic modeling. *Transactions of the ASABE,* 51**,** 2039-2049.

ZOMORRODIAN, M. A. 2012. Simulating and optimizing stormwater best management practices in University of Louisville watershed, Master's Thesis, web: https://ir.library.louisville.edu/etd/1653/.